University of Edinburgh

Geological Dept.,
6th June, 1911.

Dear Sir,

I hereby declare that the accompanying thesis for the degree of Doctor of Science has been composed by myself, and that the research, unless where acknowledgement is made in the thesis, has been carried out by myself.

I am,

Yours faithfully,

THE GEOLOGY OF SOUTH-EASTERN KINCARDINESHIRE .

BY

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------oOo------

C O N T E N T S

PREVIOUS LITERATURE.

B.N.Peach. "Fossil Myriapods from the Lower Old Red Sandstone of Forfarshire". Trans. Royal Phys. Soc. Edin. 1882.

Geological Survey, Sheets 66,67,57, and 57a; 1884: revised ed. 1897.

Sir Archibald Geikie, "Ancient Volcanoes of Great Britain" Vol. I, 1897

G. Barrow, On the occurrence of Silurian (?) Rocks in Forfarshire and and Kincardineshire along the Eastern Border of the Highlands", Q.J.G.S., 1901.

G. Hickling, "The Old Red Sandstone of Forfarshire, Upper and Lower", Geolog. Mag. 1908.

R. Campbell, "Preliminary Note on the Geology of South-eastern Kincardineshire". Geolog. Mag. 1911.

INTRODUCTION.

Although excellent maps on the 1-in. and ¼-in. scale have been issued by the geological survey, no descriptive account of the geology of south eastern Kincardine-shire has been published. Some three years ago, at the suggestion of Professor Geikie, I undertook an investigation of the volcanic rocks of the district. During the course of the research, however, several points of stratigraphical and structural interest were observed, the interpretation of which necessitated mapping the area on the 6-in. scale. In the present paper I propose to discuss the stratigraphy of the palaeozoic rocks, and to give a petrographical account of the volcanic rocks of Lower Old Red Sandstone and Carboniferous age.

AREA AND PHYSICAL FEATURES.

The area selected for investigation embraces the portion of Kincardineshire which lies to the south of the Highland fault. It is included/

included in sheet 57a and parts of sheets 57,66,and 67 of the 1-in. maps of the Ordnance and Geological Surveys.

The landscape of South-eastern Kincardineshire in its main features recalls at once the tract of the Midland valley which lies between the Sidlaws and Ochils and the Highland hills. It shows, moreover, in the same striking fashion, the interdependence of geological structure and topography. The Howe of the Mearns is the continuation the north-east of the plain of Strathmore. Occupying the central portion of the well-known synclinal fold which is the dominant structural feature, it has been carved out of the soft marls and marly sandstones which form the youngest strata in the Lower Old Red Sandstone succession in this area. On the south-east it is flanked by the Garvock Hills, a ridge built up of the more resistant lavas and coarse conglomerates. In the neighbourhood of Bruxie Hill the hard belt swings round the syncline, and is continued along the north-western boundary of the plain in the Knock Hill and the hills of Strathfinella. Between the latter and the North Esk the "Howe" is bounded by the hills of Dalradian schists beyond the Highland fault. The continuity of the ridge of the Garvock Hills is broken in two places. Through one gap flows the Water of Bervie; the other, near Marykirk, is a typical "wind gap", and is obviously a relic of some ancient river system. Particular interest is evoked by the hill, or rather group of hills, known as Strathfinella, which attain a height of from 1200 to 1358 feet. The general level of the summits, when viewed from the hills to the north, appears to be a continuation of the broad table-land which is marked by the "long level line of the Highland mountain-tops". It is not an easy matter, as/

as Sir Archibald Geikie has remarked, to fix the geological date of the denudation which produced the table-land. The evidence afforded by Strathfinella suggests that, in part at least, the period of denudation was later than the Lower Old Red Sandstone.

So far as its main elements are concerned the present landscape probably bears a close resemblance to that of the period immediately preceding the Great Ice Age. In its details, however, it everywhere bears witness to the modifying power of glacial and fluvio-glacial agencies. The rounded flowing contours of the hills, the presence of roches montonnés, glacial grooving, and "Crag and Tail", and the thickness of the mantle of boulder clay which enwraps a great part of the county all testify to the power of land ice as an eroding agent. The present streams in some parts of their courses meander in wide valleys of pre-glacial origin, in others they flow in narrow gorges of younger date. In marked contrast are the details of the topography of the ridges which bound the central "Howe". On the one hand the smooth, monotonous boulder clay-covered slopes of the Garvock Hills rise at gentle angles from the plain; on the other, along the margin of the Highlands, the surface features present a much more varied aspect. There the boulder clay of the plains is capped abruptly by thick accumulations of coarse gravel and sand which show a maximum development opposite the mouths of the valleys which open out from the Highland hills. These gravels and sands extend as flat-topped terraces far up the valleys. They were formed probably at a time when the foot-hills of the Grampians were free from ice, while a great lobe of the Highland ice-sheet still occupied the Howe of the Mearns. The hills which rise behind the gravel terraces show a beautiful succession of dry contour valleys. Indeed the occurrence/

occurrence of these "marginal" channels is one of the most striking features in the topography. Kaimes with their associated "kettle holes" are conspicuous in the central and eastern part of the plain. Frequently, too, they may be seen capping the gravel terraces already described. Between the Garvock Hills and the coast, and particularly in the district to the north of Bervie, the most note-worthy point in the physical geography is the magnificent development of glacial grooving. The direction of the ice-movement during the period of maximum glaciation coincided approximately with the direction of strike of the strata, and, as a result, the softer rocks have been hollowed out into trough-like depressions, while the more resistant lavas and conglomerates stand out in relief in a series of more or less parallel ridges. The hard, massive, conglomerates of Kincardineshire rival the igneous rocks in the way in which they influence the development of the topography.

From Stonehaven to Dunnottar Castle the trend of the coast line is at right angles to the general strike of the strata, and rock character has, therefore, played an all-important part in determining the scenic features. The numerous bays and narrow inlets are carved out of the softer tuffs and tuffaceous sandstones; the hard conglomerates stand out as bold headlands and isolated half-tide stacks. At Maiden Kaim the strike swings round parallel to the coast and southwards as far as Bervie we find a succession of lofty cliffs, sometimes rising sheer up from the sea to a height of two hundred feet, and interrupted here and there by picturesque caves and rocky bays worked out along lines of faulting and jointing. From Bervie to the North Esk the most conspicuous element in the coastal topography/

topography is the flat spread of the twenty-five foot beach with its accompanying cliff, which only at occasional intervals approaches the present shore line.

GEOLOGICAL FORMATIONS.

The palaeozoic formations of south-eastern Kincardineshire include:- (1) ? Upper Cambrian - the (?) Arenig of the geological survey maps; (2) Upper Silurian (Downtonian) - including part of the Lower Old Red Sandstone of the above maps; (3) Old Red Sandstone (Upper and Lower).

Evidence of contemporaneous volcanic activity is found in all the formations except the upper Old Red Sandstone. Certain intrusive rocks later than Old Red Sandstone are probably of Carboniferous Age.

SHORT SUMMARY OF GENERAL RESULTS.

As a result of this research the following points have been established:-

(1) The Great Highland fault is an over-thrust - not a normal fault as has been supposed.

(2) The Highland border rocks, mapped as of ? Arenig age in the geological survey maps, are ? Upper Cambrian.

(3) The "Stonehaven beds", hitherto regarded as belonging to the Lower Old Red Sandstone, are Upper Silurian (Downtonian).

(4) The Downtonian series rests unconformably on the Upper Cambrian.

(5) Volcanic activity had begun along the margin of the Highlands in Downtonian times.

(6) Well-marked volcanic horizons can be recognised, and, in the absence of palaeontological evidence, are of value in working out the stratigraphy of the Lower Old Red Sandstone series.

(7) The lavas of Lower Old Red Sandstone age belong to a typical cale/

cale-alkali series, ranging from Dacite to Olivine Basalt.
(8) The later Dolerite dykes are of the same petrographical type, and presumably of the same age as the late Carboniferous dykes of the Midland valley.

The research has included mapping of the area on the 6-in. scale, but, since the detailed mapping of the district to the west of the Bervie Water has not yet been completed, the accompanying geological map has been constructed in part from information obtained from the 1-in. maps of the geological survey.

? UPPER CAMBRIAN.

Between Craigeven Bay and Garron Point occurs a series of crushed green igneous rocks with thin intercalated black shales, jaspers, and cherts, which are shown in the geological survey maps as of (?) Arenig age. Similar rocks in the form of lenticular strips (and associated as a rule with a younger series, the Margies) occur at intervals along the south-eastern border of the Highlands. Mr. Barrow* considers that, in all the occurrences in Forfarshire and Kincardineshire, the Arenig-Margie rocks are bounded on the south by the Highland fault (which he regards as a normal fault), while on the north a thrust plane separates them from the Dalradian schists. Evidence has been obtained in the present research which proves that, in its most easterly occurrence, the jasper and green rock series lies to the south of the Highland fault, while its southern boundary is not a line of faulting, but marks an unconformable junction with the over-lying Downtonian series.
In great part the jasper-green rock series consists of crushed green igneous/

* Q.J.G.S. 1901.

igneous rocks, which resemble closely the spilitic lavas of Arenig age in the Southern Uplands; and, like the latter, they are associated with jasper, chert, and black shales. The Craigeven Bay rocks are much less intensely crushed than the corresponding groups in the North Esk section and other sections to the west. In August, 1909, on the occasion of a visit to Craigeven Bay in company with Dr. B.N. Peach and Mr. W.T.Gordon, we spent some time in searching for fossils in the above-mentioned sediments, and in the black shales we succeeded in finding organic remains, including a linguloid shell and a bivalve phyllocarid crustacean. Realising the importance of the "find" we reported it to Dr. Home of the geological survey, and the assistance of Mr. D. Tait was obtained in making a detailed search in the fossiliferous beds. Mr. Tait collected a remarkable suite of fossils which have thrown important light on the age of the rocks.

Dr. Peach, in whose hands the fossils were placed for determination, has very kindly supplied the following note:-

"The collection includes several specimens of hingeless brachiopods belonging to the genera Lingulella, Obolella, Acrotreta, Linnarssonia, and Siphonotreta; a few specimens of a bivalve phyllocarid allied to Caryocaris and Lingulocaris; cases of a tubicolar worm, the structure of the tubes being like that of the modern Ditrupa.

"Without further study it may be premature to express a definite opinion about the horizon of these fossils. The genera represented are most commonly found in the lowest division of the Lower Silurian (Ordovician) system and the Upper Cambrian. The absence of graptolites however, suggests that they may belong to the latter rather than to the lower Silurian".

Dr./

Dr. Walcott, of the U.S.geological survey, to whom the fossils were afterwards submitted, reports that he is inclined to agree with Dr. Peach's conclusion that the fauna is an Upper Cambrian one. Whatever may be the ultimate decision as to their precise stratigraphical horizon, it will readily be admitted that the fossils must determine also the age of the similar groups of green crushed igneous rocks and associated sediments, which occur at intervals along the Highland border. It has now been proved beyond the shadow of a doubt that these Highland border rocks are not pre-Cambrian. Thus, obviously, the discovery of these fossils has a very direct bearing on the fascinating, if perplexing, problems which are presented by the tectonics of the Central and Eastern Highlands.

UPPER SILURIAN (DOWNTONIAN).

At Ruthery Head, a short distance south of Craigeven Bay, what has hitherto been regarded as the Lower Old Red Sandstone formation rests unconformably on Upper Cambrian Strata. As has been mentioned above, this boundary line was formerly looked upon as marking the line of the Highland fault. And, indeed, masked as the unconformity is by minor faulting and by the red staining of the underlying rocks, it is not perhaps surprising that the basement breccia was mistaken for a fault breccia. Further: owing to the discovery of fossils in certain beds overlying the basement breccia, a considerable thickness of what was formerly mapped as Lower Old Red Sandstone must be considered as of Downtonian age. No marked discordance has been detected anywhere in the upward succession from Downtonian to Lower Old Red Sandstone. In the description of the coast section given in my preliminary paper I took the massive "quartzite" conglomerate* of Downie/

* Quartzite Conglomerate = Conglomerate in which quartzite pebbles predominate.

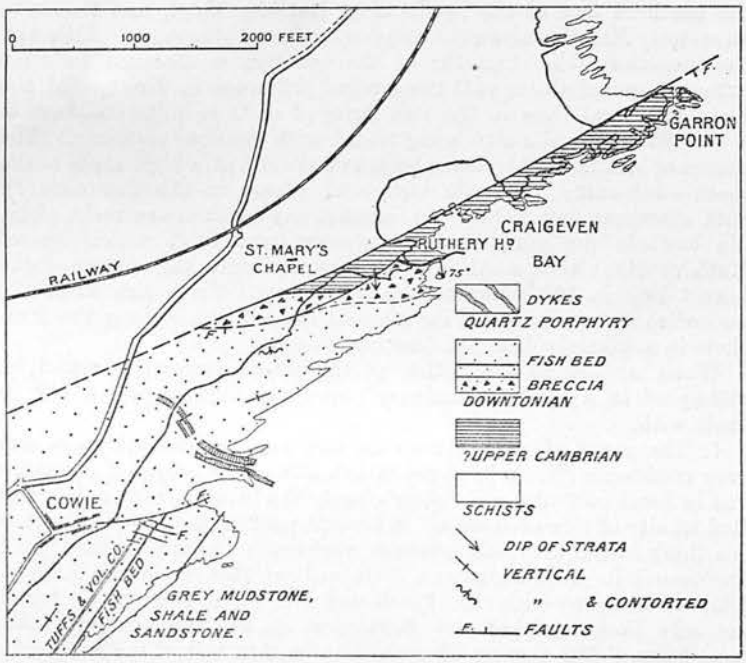
Downie Point as the base of the latter formation. After further study of the Inland sections, however, I have thought it better to include with the basal conglomerate the brown micaceous pebbly sandstone at Stonehaven Harbour along with the intervening tuffs and volcanic conglomerate. The brown micaceous sandstones contain numerous pebbles of quartzite and herald the oncoming of the first of the great quartzite conglomerates.

The succession of the Downtonian rocks as shown in the coast section from Craigeven Bay to the mouth of the Cowie water is as follows (in descending order):-

7.	Tuffs and tuffaceous sandstone	800
6.	Grey sandstone and fossiliferous sandy shales and mud-stones (with fish-band)	600
5.	Red Sandstone	60
✗ 4.	Volcanic conglomerate and tuffs	40
3.	Grey and brown sandstones with thin red mudstones	1000
2.	Purple sandstone	60
1.	Basement Breccia	200

The basement beds consist of breccias with intercalated thin red sandstones and sandy mudstones. The breccias are made up almost entirely of angular fragments of the igneous rocks and jaspers of the underlying Cambrian(?) strata, but they contain also occasional sub-angular and rounded pebbles of granite and schists. The unconformity which marks the base of the series may be traced along the northern face of the headland at Ruthery Head, and thence in an easterly direction along the foreshore to low-water mark. Although the unconformable character of the junction is obscured to some extent, as noted/

✗ "Volcanic" Conglomerate = Conglomerate in which the predominating pebbles are of contemporaneous lavas.



Sketch-map of Geology of the Coast of Kincardineshire from Cowie to Garron Point.

Fig. 1.

noted above, still the marked difference in direction of the main structural lines in the two series of rocks is quite sufficient to allow of the unconformity being traced with absolute certainty. The planes of bedding in the Downtonian strata dip at a high angle to the south-south-east; the main structural planes in the Cambrian (?) both cleavages and bedding, in igneous and sedimentary rocks alike, dip towards the north-west.

The fact that the breccias are interstratified with numerous intercalations of finely bedded sandstones and mudstones excludes their interpretation as fault breccias. An overthrust fault which crosses Ruthery Head in a north-easterly direction shifts the outcrop of the lowest breccia 160 yards to the south-west. From this fault the unconformity can be traced for a considerable distance along the foreshore in a westerly direction (see sketch-map, fig. 1).

The purple sandstones which overlie the basement breccias appear to consist mainly of finely-comminuted débris of the rocks of the Upper Cambrian Series.

Next in the succession comes a thick series of grey and brown ochreous sandstones with intercalations of pale red mudstones. The sandstones which locally contain abundant clay galls, are often markedly false bedded. The mudstones occasionally show beautiful examples of sun-cracks. On the south side of the entrance to Cowie Harbour a dip fault with down-throw to the south shifts the above series to the west. On the foreshore between Cowie and Stonehaven Bay the brown and grey ochreous sandstones are overlain by a coarse volcanic conglomerate with which is associated a belt of tuffs and tuffaceous sandstone (No. 4 in above table).

The volcanic conglomerate which has a maximum thickness of about

30 feet may be traced as a conspicuous ridge in the foreshore running in a south-south-westerly direction from Cowie Pier. As it approaches the Cowie Harbour fault it is traversed by a large number of minor dip faults, each of which shifts the outcrop slightly to the eastward as the conglomerate is followed towards Cowie. Made up almost entirely of rounded boulders of hornblende andesites and rhyolites, the conglomerate is overlain by a belt of soft red hornblende andesite tuffs with a maximum thickness of 27 feet, to which succeeds a thin bed of fine conglomerate with green tuffaceous matrix. (See Plate IV. figs. 4 & 5).

The next member in the succession is a massive red sandstone with occasional thin mudstones. It presents no feature of particular interest.

The red sandstone is overlain by about 600 feet of grey sandstones and sandy shales with green and grey mudstones (No. 6) . This group is the most important in the series since, alike in its lithological characters and in its fossil contents, it shows the Downtonian rather than Old Red Sandstone affinity of the succession. The predominant sediments are grey sandstones, occasionally rich in clay galls and in places containing bands of calcareous nodules. At intervals there occur intercalations of green and greyish sandy mudstones and shales, in which Dictyocaris is found in great abundance. The most noteworthy of the mudstone and shale groups occurs about 20 yards east of Cowie Harbour. On visiting this section in August, 1909, in company with Dr. Peach and Mr. W.T.Gordon, we found not only Dictyocaris, but also Eurypterus sp. and fragmentary plant remains, and in a thin bed of reddish sandy mudstone, immediately overlying the red sandstones (No. 5), Mr. Gordon discovered several fish

Plates/

plates. Some of the fish fragments were suggestive of Birkenia. Mr. Gordon and Dr. Peach joined me again during the past summer in order that we might try to get material sufficient to establish the horizon of this fish fauna. Considerable additions were made to the finds of the previous summer. The fishes were submitted to Dr. R.H.Traquair who has undertaken the description of new species, and who has been good enough to send me the following preliminary note:-

"The fish remains from Cowie, Stonehaven, consist of -

"First: Small scutes which are about three times as long as they are broad, slightly convex on one side and correspondingly concave on the other, and apparently pointed at both ends. They seems to me to be referable to the category of Cephalaspidian scutes, only the external ornament, where visible, consists of longitudinal and slightly wavy striae in place of tubercles. That the species to which they belong is as yet unnamed and undescribed is pretty certain, but the advent of additional material is desirable before proceeding further in that direction.

"Second: Several fragments of thin, minutely tuberculated plates which may also be Cephalaspidian, though their nature is indeed problematical.

"Third: Two median plates of a beautiful new Cyathaspis.

"The specimens from the grey sandstones over-lying the fish-band consist of irregular blackish and reddish blotch-like films, which, on examination with a lens, show in many cases a honeycomb-like marking, consisting of minute polygonal areae, whose margins are on one side of the stone raised, on the counterpart incised. These markings are at once suggestive of the middle layer of the Pteraspidian/

pidian shield, but in none of the specimens is any trace found of the inner layer or of the outer layer with its markings. More likely does it seem that these films are of the same nature as the problematic Dictyocaris of Salter from the Upper Silurian of the Pentland Hills, which occurs in similar blotch-like masses and shows very similar polygonal markings.

"As to whether the Cowie fish-remains indicate a Lower Devonian or an Upper Silurian (Downtonian) horizon, they in themselves afford no certain answer to the question, beyond this, that Cyathaspis, although it occurs in Lower Devonian rocks, seems, according to number of species, to be more characteristically a Silurian genus.

If, therefore, the associated invertebrate remains favour the reference of these beds to the Downtonian horizon, that idea would be corroborated rather then the reverse by the relics of fishes noted above".

Dictyocaris, unfortunately, must still be labelled "incertae sedis".

From its resemblance to the living Marchantia it was thought it might possibly be a plant, but Dr. D.H.Scott, to whom specimens were sent for determination, replied that, in his opinion, they were not vegetable. Dr. Smith Woodward of the British Museum thought that they were unsatisfactory fragments of the dermal armour of Cephalaspidian and Pteraspidian fishes, and a larger collection of specimens was made and submitted to Dr. Traquair along with the undoubted fish remains. Dr. Traquair is of opinion that it is not likely that the fossil can represent the median layer of the Pteraspidian shield, although the resemblance is a suggestive one. There can be no doubt, however, that the Cowie specimens are identical with the Dictyocaris

of/

of Salter, which occurs in the Upper Silurian of the Southern Uplands and in the English Downtonian.

Apart from plant-fragments, worm-tracks, and Dictyocaris the remaining fossils belong to the Arthropoda. They include Ceratiocaris sp. (carapace, rostrum, and cercopod); Archidesmus sp. and a new genus of Myriopod; (?) larval form of insect; Eurypterus, sp. nov.; fragments of scorpion. These Arthropoda will be described by Dr. Peach, to whom I am indebted for the above provisional determination.

The highest beds in the Downtonian series (No. 7) consist of green and red tuffs and brown tuffaceous sandstone with occasional intercalations of pebbly bands and thin sandy mudstones. They are exposed on the foreshore at Stonehaven Bay, but can be studied only when the tides are low.

Inland, on account of the drift-covered character of the country, the succession cannot, of course, be studied in the same detail.

Fortunately, however, in sections in the Carron Water and its tributaries, in railway cuttings, and in occasional quarries, evidence has been obtained which has enabled me to map the Downtonian series for about seven miles to the west. The general strike of the series is parallel to the Highland fault, while the strata are highly inclined with dip to the south-south-east. Locally, as may be seen in the coast section, there is inversion, and the beds dip towards the fault. It is quite clear, however, that from the mouth of the Cowie Water to the basement breccia we are dealing with a descending succession. From the coast to the neighbourhood of Elfhill the Downtonian rocks form the lowest strata in the steeply-inclined northern limb of the Strathmore syncline. Westwards from Elfhill there/

there is a tendency to set up a steep-limbed anticline pitching out to the south-west against the Highland fault, and from Elfhill to the Carron Water just west of the farm of Waters the Downtonian series occupies the core of the anticline.

No very useful purpose would be served by describing in detail the various inland sections.

The volcanic conglomerate with its associated tuffs (No. 4), and the fossiliferous green and grey mudstones of No. 5 have been traced at intervals for about six miles to the west of Stonehaven, They keep the same relative position, their lithological characters are constant, and Dictyocaris continues to be the characteristic fossil.

Both zones may be recognised in the Carron Water between Carron Lodge and the bend of the river opposite Dunnottar Church. Just west of the church the series is traversed by an important fault, which extends from Thornyhive Bay to the Highland fault near Fetteresso saw-mill. The outcrop of the fossiliferous beds is shifted to the north-west. Re-appearing in the Cheyne Burn near the saw-mill they may be traced west-wards, and are found in the Burn of Graham a short distance below Bridge of Graham, on the Carron Water about half a mile west of Tewel, and again on the Carron Water at its junction with the Elfhill Burn. The volcanic conglomerates and tuffs are best seen in a splendid strike section in the Elfhill Burn. They are also exposed in the Burn of Graham.

From the section on the Carron west of Tewel Mr. D. Tait obtained a fish spine, and, since the green mudstones there are associated with a reddish sandy mudstone, which, lithologically, is identical with the band which yielded the fishes at Cowie, it is hoped that careful/

careful search in this locality will yield further specimens belonging to the Cowie fish fauna. In a quarry near the schoolhouse of Tewel a curious mottled sandstone is in places richly charged with plant remains, none of which unfortunately, are determinable.

On returning from Stonehaven last summer I learned from Dr Horne that in 1881 Mr MacConnochie, of H.M. Geological Survey, collected from the "Stonehaven Beds" on the shore near Cowie, and from the prolongation of the same beds exposed in the Carron Water, west of Tewel, specimens of Dictyocaris, together with fragments of Pterygotus, Eurypterus, and (?) Kampecaris. From the abundance of the remains of Dictyocaris Dr Peach at that time suggested that the beds containing these fossils might be of Upper Silurian age.

Although the typical Downtonian fishes of the south of Scotland have not so far been met with in Kincardineshire, yet the occurence of Ceratiocaris and Dictyocaris, neither of which has hitherto been found in rocks younger than Upper Silurian, would appear to indicate that these Cowie beds are of Downtonian age. This view, as pointed out by Dr Traquair, is apparently corroborated by the association of these fossils with Cyathaspis.

CONDITIONS UNDER WHICH THE DOWNTONIAN SERIES WAS DEPOSITED AND COMPARISON WITH THE DOWNTONIAN OF THE SOUTHERN UPLANDS.

On my first visit to the Cowie section the point which appealed to me most strongly was the marked dissimilarity between the type of sedimentation which the rocks exhibited compared with the normal "Old Red" sedimentation which is seen everywhere alse in the coast section/

section. And, when, afterwards, under the guidance of Dr Peach I had seen the splendid sections in the Downtonian of Lanarkshire, it became clear at once that, as far as lithological evidence went, the Cowie beds bore the impress of a Downtonian rather than a normal Old Red type of sedimentation. In Kincardineshire just as in the Southern Uplands the Downtonian rocks form what is truly a transition series, in some respects exhibiting the characters of a normal Upper Silurian set of sediments, in others those of the Lower Old Red sandstone. To the former belong the green and grey mudstones and the greywacké -like sandstone, to the latter the coarse conglomerates and the false-bedded ochreous sandstones. In the Southern Uplands* the fossil evidence indicates that the green and grey mudstones, the greywackés, and the fish band are marine. They have yielded species of eurypterids, which, in the Wenlock series are associated with graptolites, in the Ludlow series with a Lingula; moreover they contain Glauconome, Spirorbis, and sponges. The rock types which resemble the Old Red Sandstone sediments, on the other hand, have been supposed to indicate fresh or brackish water conditions. In Kincardineshire no evidence has been obtained so far which would point conclusively to marine conditions. No undoubtedly marine organism has been found, and the association of the eurypterids with plant remains, scorpion fragments, galley-worms, and a larval form of insect appear to indicate that the green and grey mudstones were laid down in close proximity to a land area, and at the most, can imply only estuarine conditions; the interbedded ochreous sandstones with their characteristic false-bedding and the development/

* "The Silurian Rocks of Scotland" p. 68.

development of sun-cracks in the red sandstones point conclusively to shallow water conditions of deposit. The coarse volcanic conglomerate, like these of the Old Red Sandstone, in most likely a torrential flood gravel.

In the Southern Uplands the Downtonian series passes down conformably into the Ludlow. The presence of quartzite conglomerates shows that the sediment, in part at least, was derived from the Highland area. At Cowie the Downtonian rocks rest unconformably on the ?Upper Cambrian, while, as we shall see when we consider the Lower Old Red Sandstone succession, there is probably a marked overlap as the series is traced over the Highland area to the west. Again, in Kincardineshire the Downtonian series passes up conformably into the Lower Old Red Sandstone; in the Southern Uplands it has been found that the two series are separated by an unconformability in the Pentland Hills and Ayrshire, while in Lanarkshire there is an "apparent conformability", the basal conglomerate of the Lower Old Red Sandstone series being made up everywhere mainly of boulders of greywacké derived from the rocks of the Silurian tableland. Consideration of the above facts suggest that.

(1.) During Downtonian times there was continuous subsidence of the central valley accompanied no doubt by a movement of elevation in the Highland area, the basement members of the Downtonian series gradually overlapping the older rocks and at Cowie, as we have seen resting directly in the folded ?Upper Cambrian.

(2.) Over the southern part of the area towards the close of the Downtonian/

Downtonian period the movement of subsidence was interrupted for a time, the Silurian strata including the Downtonian being subjected to great lateral compression and thrown into a series of folds, giving rise to an elevated region, the denudation of which supplied the material for the formation of the basement conglomerate of the Lower Old Red Sandstone. Over the northern part of the area, on the other hand, the subsidence was continuous during the whole of the Downtonian and Lower Old Red Sandstone periods.

One aspect of the Downtonian succession remains to be considered, namely the evidence of contemporaneous volcanic action. In the Southern Uplands no contemporaneous volcanic rocks have been found in the Downtonian series, the earlier lavas and tuffs invariably overlying the basement greywacke conglomerate of the Lower Old Red Sandstone Series. Sir Archibald Geikie* has correlated the initial outbreak of volcanic activity in "Lake Caledonia" with the coming on of the conditions which gave rise to the lowest of the massive quartzite conglomerates. That volcanoes were active in this region at a much earlier period is seen from the great development of tuffs and volcanic conglomerate in the Downtonian sequence. The lowest volcanic conglomerate is about 2500 feet below the above-mentioned quartzite conglomerate. The predominating constituents of the volcanic conglomerates are hornblende andesites, and felsites. As we have already seen, the lowest zone of volcanic conglomerates and tuffs, can be traced inland until it is lost against the Highland fault, and, since there is abundant evidence to show that/

* "Ancient Volcanoes of Great Britain", Vol. I p. 303.

that the material of all the associated sediments was derived from the Highland area, one must conclude that, early in Downtonian times, (or perhaps in pre-Downtonian, but subsequent to the movements which folded the eastern schists), acid andesites and rhyolites flowed out in abundance from a volcanic centre situated somewhere in the schist and granite country to the north of the Highland fault.

LOWER OLD RED SANDSTONE.

The rocks of Lower Old Red Sandstone age, which occupy the greater part of south-eastern Kincardineshire, include coarse conglomerates, sandstones, and marls interbedded with lavas, tuffs, and volcanic conglomerates. The enormous thickness of the groups of contemporaneous volcanic rocks points to a prolonged period of volcanic activity, which, as we have seen above, had been initiated at least as far back as the beginning of Downtonian times. Resting conformably in the Downtonian series, the Lower Old Red Sandstone is in turn overlain by rocks of Upper Old Red Sandstone age. The latter are found in Kincardineshire in a small area along the coast between East Mathers and the mouth of the North Esk, and the junction between the two series is probably everywhere a line of faulting. Near Arbroath, however, the Upper Old Red Sandstone rests unconformably on the Lower, and, as Mr Hickling* has clearly shown, the latter series had undergone extensive folding and denudation before the deposition of the former.

In Kincardineshire, as elsewhere, one noteable characteristic of/

* Geolog. Mag. Dec. V. Vol. V. No IX. 1908.

of this formation is the paucity of organic remains. A few additions to our knowledge of the fossiliferous localities have been made in the course of the present research, but the palaeontological evidence is so meagre that it has been found of little value for stratigraphical purposes. Lithological evidence, on the other hand obtained from conglomerates, lavas, and tuffs, and, in particular, the recognition of a well-marked succession in the lavas, has aided materially in elucidating the structure of the area occupied by the Lower Old Red Sandstone.

The rapid variation of the sediments from point to point along any given horizon makes it almost impossible to draw a sharp line of demarcation between one zone and another. For convenience of description, however, the succession may be arranged as under, the various subdivisions being given in descending order :-

(e) The ~~red marl~~ Strathmore group.

(d) The Garvock group.

(c) The Arbuthnott group.

(b) The Crawton group.

(a) The Dunnottar group.

(a) THE DUNNOTTAR GROUP.

The Dunnottar group includes the part of the Lower Old Red Sandstone which lies between the base of the series and the top of the Tremuda Bay lavas. A brief description of the coast section from Stonehaven to Thornyhive Bay will perhaps serve to indicate the general aspect of this portion of the Old Red succession. Its chief/

chief characteristic is a magnificent development of coarse quartzite conglomerates with intercalated thin brown sandstones. In the conglomerates well-rounded quartzites are always the most conspicuous constituent. They are accompanied by other "Highland" rocks and by a varying proportion of granites, quartz porphyries, rhyolites, and acid andesites. Boulders derived from the Jasper-Green rock series are present as a rule in great abundance, but, in the conglomerates underlying the Tremuda Bay lavas, they are almost entirely awanting, their place being taken by an abnormally large number of rhyolites and acid andesites. Locally, too, and particularly in the conglomerate just south of Strathlethan Bay, boulders of a coarse grit resembling the "Haggis rock" of Caradoc age of the Southern Uplands are fairly numerous.

At four horizons the conglomerates are interbedded with contemporaneous volcanic rocks.

(1) At Stonehaven harbour the basement members of the group, brown micaceous pebbly sandstones, are separated from the coarse quartzite conglomerate of Downie Point by a considerable thickness of acid tuffs with a few bands of coarse volcanic conglomerate.

Three lavas are indicated in the geological survey map as occurring in the vicinity of Stonehaven harbour, but I have been able to find only one crystalline igneous rock and that an intrusive quartz dolerite.

(2) In Strathlethan Bay the Downie Point conglomerate underlies a series of soft tuffs and tuffaceous sandstone, with which again are associated volcanic conglomerates. Here, too, we find the lowest/

lowest lava flow of Old Red Sandstone age in Kincardineshire - an augite andesite. It forms the small island of Carlin Crag, but is truncated by a fault and does not appear in the cliff section.

(3) After a long interval, represented by a great thickness of conglomerates, another zone of acid tuffs is found in Old Hall Bay, just south of Dunnottar Castle.

(4) At Tremuda Bay the highest members of the Dunnottar group include a series of at least six flows of olivine basalt of a coarsely crystalline, doleritic type. Each flow consists of a massive central portion with well-marked scoariaceous upper and under surface; the second shows good columnar structure. The slaggy upper surfaces occasionally enclose "veins" of sandstone. The bottom lava has flowed over a bed of soft mud, portions of which have been caught up in the lower scoriaceous surface. At the north side of Thornyhive Bay its lavas are truncated by the important fault already alluded to, and the top of the series is not seen.

The lava near the lighthouse at Tod Head Point is a doleritic basalt of the same type as the above, and, along with the underlying conglomerates, may be considered as belonging to the Dunnottar Group. It shows a very slaggy upper surface with the characteristic sandstone veinings, and is described and figured in Sir Archibald Geikie's "Ancient Volcanoes", Vol 1. p. 303.

Inland sections are sufficiently numerous to show that, along the steeply inclined northern limb of the Strathmore syncline, the Dunnottar group maintains the same general characters which it exhibits/

exhibits in the coast section. Quartzite conglomerates predominate, but at intervals there occur acid tuffs and volcanic conglomerates. On the south-eastern slope of Carmont Hill, near Square's Knap, a vesicular augite andesite is associated with a coarse volcanic conglomerate, and, although the lava is not quite of the same type as the andesite of Carlin Crag, it seems fairly certain that it is in the same volcanic horizon as the Strathlethan Bay zone.

The only fossils obtained from the Dunnottar group are specimens of Parka sp. collected from a grey sandstone associated with the tuffs at Strathlethan Bay. From Stonehaven harbour to the middle of Old Hall Bay the general direction of strike is east-north-east, and west-south-west, while the strata are vertical or very highly inclined, In the section in the foreshore in the southern half of Old Hall Bay the angle of dip falls very rapidly until at the extreme south corner it averages about 35°. South of the next important headland, Maiden Kain, the beds swing round the great synclinal fold of Strathmore, the strike changing to north-west and south-east, and the average angle of dip falling to 25°.

(b) THE CRAWTON GROUP.

The Crawton group is characterised by a marked increase in the proportion of volcanic rocks, quartzite conglomerates no longer predominating as in the underlying series. Detailed mapping has shown that it presents markedly different suites of lavas on the two sides of the Strathmore syncline. The area occupied by the northern limb of the fold contains a fine development of acid andesites;

along/

along the southern limb there occurs a remarkable group of porphyritic basalts.

(1) THE CRAWTON BASALTS AND ASSOCIATED ROCKS.

The predominating type of lava in this series is a basalt with large tabular phenocrysts of plagioclase, which closely resembles the well-known Carnethy "porphyry" ofthe Pentland Hills. We shall refer to it as the Crawton type of basalt. The most southerly exposure of the Crawton basalts is seen on the shore about a mile south of Gourdon, where they are striking seawards in a north-west and south-east direction. Swinging round somewhere abruptly near Nether Knox they return to the north-north-east and south-south-west direction of strike which is the general strike of the synclinal fold. They may be followed along the higher slopes of Gourdon Hill and ultimately crop out in the Water of Bervie near Pitcarry Mills. There they are truncated by a fault, the line of which is marked by a thick fault breccia which forms a prominent wall-like feature in the left bank of the river. Reappearing in the north side of the above fault near Mill of Bervie the Crawton basalts form the lower of the two prominent rock features of Bervie Brow. As they are followed northwards it is found that, just west of Grange and again a short distance east of Wardend, the continuity of their outcrop is interrupted by two faults, which have the effect of shifting it successively further to the east. Good exposures of the basalts are seen in the old quarries in Whistleberry Wood, and the group may be followed in a northerly direction for about a mile and a half until it is again traversed by a dislocation - the Braidon Bay fault - which/

which shifts the outcrop out to sea on the ~~Downtonian~~ down throw side. The direction of strike, however, again changes as the beds begin to swing round the synclinal fold, and the characteristic Crawton basalts reappear on the coast section at the village of Crawton, where they attain their maximum thickness. From Crawton their outcrop may be followed in a north-north-westerly direction parallel to the coast to Gallowton, when, interrupted by a fault, it swings abruptly round to the east, and the group comes back to the coast at Thornyhive Bay. On the northern limb of the syncline the Crawton basalts appear in the Glaslaw Burn and may be traced ~~in~~ towards the south-south-west in bare rocky knolls in the fields almost as far as Upper Criggie.

On the shore section near the village of Crawton it can be seen that the Crawton type of basalt occurs in three successive flows, each with a slaggy upper and under surface and a massive, columnar central portion. The parallel arrangement of the tabular felspars imparts to the rock a marked platy structure. The lowest flow shows a somewhat unusual type of weathering. On a gently sloping rock platform, which has been carved out in the massive portion of the flow between low and high water marks, the sea has worked out a regular series of potholes, each of which coincides in position with the centre of one of the hexagonal basalt columns. Apparently some agency acting along the joints has hardened the margins of the columns, while the centres have been left an easy prey to the eroding action of the sea. In many places the vesicular surfaces of the Crawton/

Crawton lavas show the characteristic sandstone-veinings. But perhaps the most striking feature of the group is the evidence which it everywhere gives of contemporaneous erosion. This is particularly well seen at the top of the highest flow at Crawton. The overlying conglomerates are seen to rest on an irregular eroded surface of the lava. Sometimes the slaggy top of the latter has been entirely removed, and the pockets of conglomerate rest directly on the massive central portion. The eroded hollows coincide in position with prominent joint fissures, which are seen to narrow as they are traced downwards, and to be occupied by successively finer and finer pebbly sandstones until they end off in minute cracks filled with very fine silt. Obviously the lavas had cooled and consolidated before the advent of the currents which carried out the work of erosion. Although the overlying conglomerates contain occasional large slaggy boulders of the Crawton basalt, still the proportion of such boulders is remarkably small, and certainly does not suggest that the conglomerates have been derived by wave action from an old shore cliff of Crawton lava. To this point we shall return later. Meanwhile it may be noted that the restriction of the Crawton basalts to ~~the~~ one definite horizon, coupled with their occurence as boulders in the overlying conglomerates has been of great service in mapping the latter.

Associated with the basalts of the Crawton type are other basalts which will be described in detail later. The most widespread is a type, sparingly porphyritic with olivine and angite, which overlies the normal group from Crowhillock, Kinneff to Gallowton. ~~Occasionally~~/

Occasionally, too, there are small intercalations of coarsely crystalline non-porphyritic basalts, for example at Bervie Brow and Whistleberry; and in the Glaslaw Burn section the highest flow is a basalt with porphyritic plagioclase, olivine, and angite. These associated lavas also exhibit evidence of having undergone contemporaneous erosion.

Between the porphyritic basalts and the base of the Crawton group there intervenes a series of volcanic conglomerates, tuffs, and "Highland" conglomerates*, with one small intercalation of basic andesites or basalts near Whistleberry Castle.

The tuffs and volcanic conglomerates attain their maximum development between Bervie Bay and Whistleberry. In that tract, indeed, the "Highland" conglomerates play quite a minor part. The tuffs are built up essentially of angular and subangular fragments of hornblende and biotite andesites and felsites, the andesites always predominating. Locally they contain in abundance angular pieces of a green rock which resembles the spilitic lavas of the Upper Cambrian series. They are frequently calcareous and weather with characteristic honeycombed and furrowed surfaces. Like the tuffs, the volcanic conglomerates consist mainly of the débris of hornblende and biotite andesites. A noteworthy feature is the large size of the well-rounded boulders of hornblende andesite - a section across one in a conglomerate near Shieldhill measured 9' x 10'. The relative proportion of boulders and matrix is variable, but the latter, which has much the same composition as the associated tuffs is/

* "Highland Conglomerates" = Conglomerates whose predominating pebbles are derived from the Highland area.

is always more abundant than in the "Highland" conglomerates. The latter are characterised as usual by the almost bewildering variation in their composition as any one particular bed is traced from point to point. As a rule they contain a fair proportion of volcanic rocks belonging to Old Red Sandstone types. But the feature which, despite the extraordinary variety of the constituents, always arrests one's attention, and which serves to distinguish the "Highland" conglomerates of the~~ir~~ is group from all the others, is the abundance of boulders derived from the Upper Cambrian series. The boulders of green spilitic lavas are often so numerous as to impart a general greenish hue to whole belts of the conglomerate. The occurence of "Haggis rock" boulders is also noteworthy. At many points, and particularly in the vicinity of Shieldhill, excellent examples of contemporaneous erosion can be seen where these conglomerates rest on an uneven surface of tuffs and volcanic conglomerates.

To the north and south of the Bervie-Whistleberry tract there is a marked change in the character of the sediments which lie between the Crawton basalts and the base of the group. The tuffs and volcanic conglomerates play a smaller and smaller part in the succession as they are traced in either direction from the above centre, and their place is taken by conglomerates in which "Highland" rocks predominate and by brown tuffaceous sandstones. The lowest conglomerates in the neighbourhood of Tod Head Point contain a ~~big~~ large proportion of basic lavas derived perhaps from the contemporaneous erosion of the underlying Tremuda Bay series of basalts. At a high-

er/

higher horizon, and separated from the above by a bed of acid tuff, a somewhat remarkable conglomerate forms the cliffs below Hallhill. It contains large scattered boulders in a tuffaceous matrix. One rounded boulder of acid andesite measures in section 14' x 9'; quite near it is another of green schistose grit measuring 7' x 5' x 3'. Two points are noteworthy - the exceptionally large amount of "matrix" and the occurence together of unusually big boulders of "Highland" rocks and acid andesites. Detailed descriptions of conglomerates, however, are not in themselves of much interest, and, as has been already noted, the two main results arrived at from a study of the conglomerates of this group are :- (1) the predominance of volcanic conglomerates in the Bervie-Whistleberry tract with a gradual transition to north and south to non-volcanic conglomerates; (2) the abundance in all the "Highland" conglomerates of boulders derived from the green rocks and jaspers of Upper Cambrian age.

The lava flow near Whistleberry Castle is of particular interest since it shows, better perhaps than can be seen elsewhere in Kincardineshire, very characteristic "sandstone veining". Through practically its whole thickness it is traversed by sandstone veins and by large irregular patches of finely-bedded sediment. It recalls the fine examples from the Turnberry shore described by Sir Archibald Geikie*.

In the series underlying the Crawton lavas there is also a noteworthy development of minor intrusions in the form of decomposed lamprophyres which occur sometimes in the sills, sometimes in narrow/

* "Ancient Volcanoes of Great Britain" Vol. I p. 333.

narrow dykes, too small to be shown in the 1-in map. They are restricted to this horizon.

(2) THE BURN OF GUINEA ANDESITES AND ASSOCIATED ROCKS.

We have seen above that the Crawton basalts may be traced along the northern limb of the syncline as far as Upper Criggie. Further to the west we find another volcanic group occupying approximately the same horizon, but showing an altogether different assemblage of lavas. Basalts are represented by two, or at most three, small flows, and those markedly different from the Crawton type. The predominating types are acid andesites.

Appearing first near Temple of Fiddes - about a mile west of Upper Criggie - this volcanic zone may be followed a short distance beyond Collieston. Then for about two miles the solid geology is completely obscured by a great thickness of drift. Just west of Drumlithie similar lavas again begin to make their appearance, and, continuing with an east and west strike, they cross the Bervie Water beyond Hawkhill. Again for a short distance they are concealed under a thick deposit of boulder clay, but swinging round the Elfhill anticline, they return to the Bervie Water at the Horse Pot. Then for about a mile they are concealed under drift. They reappear, however, on the northern limb of the anticline in the Burn of Guinea, and, again swinging round a synclinal fold which succeeds the anticline, they are finally lost against the Highland fault. North of the fault, however, in the extreme west of the area a series of lavas, exposed in the Kirkton Burn and other stream sections, and mapped/

mapped as intrusive porphyrites on the geological survey map, belong to types which are identical with the Burn of Guinea hornblende andesites. It is extremely likely that these belong also to this horizon

At the bottom of this volcanic zone occurs a group of dacites extending from East Kinmouth to the Water of Bervie and forming for a considerable distance the northern bank of a remarkable dry valley. I was unable to find any exposure showing the nature of their contact with the adjacent strata, and I ~~have~~ had doubts as to whether they might not be intrusive. But, since they show everywhere very fine fluxion structure, and since dacite boulders almost identical in character make their appearance in the overlying conglomerates, they are in all probability lavas.

The lavas coloured in the map as hornblende - biotite andesites include normal hornblende - biotite andesites with phenocrysts of plagioclase, hornblende, and biotite, and compact non-porphyritic types which are somewhat more basic in character, but which on microscopic examination are seen to contain patches of magnetite which represent resorbed hornblende and biotite.

The basalts which are found intercalated with the above series between the Bervie Water and Drumlithie include a dolerite type, and a black compact hypocrystalline type with porphyritic olivine.

The widespread occurrence of boulders of the hornblende - biotite andesites in the overlying conglomerate shows that this volcanic group underwent extensive contemporaneous denudation, and a very/

very fine example of an eroded lava surface with the overlying conglomerate is seen in a small quarry at Harlingtongue.

Owing to the paucity of exposures but little can be made out regarding the sediments associated with the above lavas. On the Bervie Water at Burn of Guinea farm there is a fine section of a coarse "Highland" conglomerate with boulders of quartzite, granite, granophyre, quartz porphyry, and schists. Conglomerates of the same type occur in the Pilketty Burn and in Kinmouth Den. At Whitehill quarry, near Bogincabers, the lavas overlie a tuffacous sandstone.

(c) THE ARBUTHNOTT GROUP.

In the Arbuthnott group, as in the last, we find a markedly different assemblage of rocks on the two sides of the Strathmore syncline. In the south-eastern part of the area it includes the thickest and most widespread of the lava belts; in the north and west its chief member is a remarkable volcanic conglomerate.

(1) THE HYPERSTHENE ANDESITE AND HYPERSTHENE BASALT SERIES WITH THEIR ASSOCIATED SEDIMENTS.

As will be seen from the accompanying map the hypersthene andesites and hypersthene basalts, with occasional intercalations of sandstone and conglomerate, may be followed continuously along the southern limb of the syncline from the North Esk to Bruxie Hill, where they swing round and continue along the steeply-inclined northern limb as far as the Stonehaven - Laurencekirk Road. Then, like the hornblende andesites of the Crawton group, they are lost sight of for nearly two miles, concealed doubtless under the thick mantle/

mantle of drift which here completely obscures the solid geology. Reappearing again at the Knock Hill they may be followed as occasional flows intercalated in the volcanic conglomerates along the slopes of the Haerscha Hill to Paldy Fair Den. Then, swinging round the Elfhill anticline they cross the Bervie Water between Dellavaird Ford and Tipperty. Between that stream and the Highland fault they are again concealed under the drift. This group of lavas undoubtedly thickens towards the south and east.

If we include a few intercalated flows of doleritic basalt which occur chiefly at or near the base of the series, the lavas of the Arbuthnott group form an assemblage of types altogether different from those found in any other part of the Lower Old Red succession in Kincardineshire. Detailed descriptions of these will be given later, but meanwhile it may be noted that they are mainly hypersthene - bearing andesites and basalts. At one extreme we find normal hypersthene andesites without olivine; at the other, hypersthene basalts containing much olivine and very little hypersthene. Numerous transition types are characterised by varying proportions of the above two constituents.

Like the similar types in the Ochils and Cheviots these hypersthene bearing basic lavas are remarkably ~~not~~ rich in chalcedony, fine red veinlets of which are usually to be found ramifying through the rock in every direction, while the vesicular portions of the flows yield beautiful examples of agates in great variety and abundance. It is on this horizon at Usan on the Forfarshire side of the Montrose/

Montrose anticline that the vesicular lavas occur which yielded many of the finest specimens in the Heddle collection.

Evidence of contemporaneous erosion has not been observed at this group except in one of the lowest flows near Ste Cyrus. The slaggy upper portions often show in characteristic fashion the well-known "sandstone-veinings", the material of the veins consisting usually of hardened, green, fine-grained, micaceous sediment. Occasionally the green veins show curiously contorted bedding; they exhibit also vesicular structure, the vesicules being filled with agate material similar to that found in the adjacent lava.

In Paldy Fair Den I have mapped a flow which possesses somewhat unusual characters. It is, or at least it had been originally, a very vesicular glassy type with abundant phenocrysts of plagioclace and scattered phenocrysts of hypersthene and angite. Glassy types do not occur elsewhere in the group. But its most striking character is the abundance of xenoliths of rounded boulders mainly of hornblende andesites; in places the xenoliths are so numerous that the rock might be mistaken for a volcanic conglomerate. The enclosed blocks are similar to the boulders in the underlying conglomerate. Probably the xenoliths were collected by the lava as it flowed over an unconsolidated gravel.

At the base of the group everywhere along the southern limb of the syncline we find a very coarse "Highland" conglomerate whose chief constituents are well-rounded quartzites. Locally it contains boulders of the underlying basalts. Comparing it with the "Highland " conglomerates/

conglomerates of the Crawton group we notice at once a marked decrease in the proportion of boulders derived from the jasper-green rock series. This zone of coarse conglomerate is succeeded by a belt made up of finer conglomerates, associated with sandstones and flaggy beds; sometimes the sandstones, sometimes the fine conglomerates predominate. This belt may be traced along the strike by a line of quarries mostly now disused. Three Wells Quarry, near Bervie, is still worked, and there I was fortunate enough to find a good specimen of Cephalaspis Lyelli. As the base of the lavas is approached we begin to find, particularly in the north-eastern part of the area, intercalations of the volcanic conglomerates and tuffs which occupy almost the whole thickness of this group along the northern limb of the syncline.

(2) THE VOLCANIC CONGLOMERATES AND TUFFS.

The volcanic conglomerates and tuffs which occur at intervals interbedded with the ordinary conglomerates and sandstones along the southern limb of the syncline attain a considerable thickness in the vicinity of Law of Lumgair. It should be noted, however, that the width of the outcrop there is in great part accounted for by the low angle of ~~the~~ dip. From Mid Fiddes westwards they form almost the whole thickness of the Arbuthnott group, taking the place which is occupied by the hypersthene andesites and basalts and the ordinary sediments in the south-eastern part of the area. Their base rests on the hornblende andesite of Harlingtongue, and their upper limit is found a short distance above the top of the Knock Hill lavas/

lavas. Westwards from the Knock Hill the top of the series may be traced in an east and west direction as far as Glensaugh, while the basal members swing round the Elfhill anticline, and, as we have seen, along with the accompanying andesites cross the Bervie Water near the Horse Pot, Dillavaird. Near the Ford of Dillavaird the beds strike north and south and dip towards the west at an angle of 30°. In the neighbourhood of Drumtochty Castle the direction of strike is almost east and west, and, consequently, at Glensaugh the series is almost entirely cut out by the Highland fault. The direction of strike changes again to south-west and north-east, and a very fine section of the volcanic conglomerates and their associated tuffs is seen in the Ferdun Burn at the Clatterin' Brigs. There, although the base of the series is not seen, it attains a thickness of about 2000 feet. From the Clatterin' Brigs westwards these rocks may be hammered in almost every stream section, until, the direction of strike changing gradually to west-south-west and east-north-east they are eventually lost against the Highland fault about half a mile from the river North Esk.

Representative collections of boulders from these conglomerates at various horizons show that the boulders consist almost entirely of acid andesites and rhyolites. A big percentage of the former belongs to types found in the acid andesite zone of the Crawton group. One boulder of silicified rhyolite shows the same type of silicification as the rock from Camp Hill Quarry in the Pentlands (see Memoir of Edinburgh District. Plate x figs. 1 - 2) None of/

of the basic andesites or basalts are represented in the collections made from these conglomerates along the Highland border. Sometimes the volcanic conglomerates are built up entirely of the débris of acid volcanic rocks, but more frequently they contain a small percentage of boulders derived from the Highland schist series - a point which is of interest in showing that the material was being derived from the area to the north of the Highland fault. Locally too, there occur thin conglomerates of the "Highland" type, but such form an insignificant part of the succession. The volcanic conglomerates are associated invariably with interbedded "tuffs". While some of the latter may have been derived from an already consolidated series of lavas by the ordinary agents of denudation, numerous occurrences have been noted in which the sharply angular nature of the constituent fragments clearly shows that they are true pyroclastic tuffs. These tuffs are rhyolites rather than andesites and in this way differ from the tuffs associated with the Crawton group. Excellent examples occur in the Bervie Water near the Ford of Dillavaird, and in the Shag Burn opposite Honeybank. The tuffs are not separated from the volcanic conglomerates on the accompanying map, but they make up no inconsiderable part of the whole series.

Indeterminable plant fragments, found in a thin intercalation of grey micaceous shales near the Ford of Dillavaird, are the only fossils which I have noted in this part of the Arbuthnott group.

(d) THE GARVOCK GROUP.

This group consists for the most part of coarse "Highland" conglomerates/

conglomerates with intercalated grits, sandstones, flagstones, shales, and limestone. It includes also the highest of the lava zones.

The main group of lavas extends from the North Esk near Marykirk to Cairn of Shiels. A minor group at a slightly lower horizon occurs on either side of the Bervie Water near Whitefield. The lavas are all basalts, occasionally with phenocrysts of olivine but more usually coarsely-crystalline, non-porphyritic doleritic types. The slaggy surfaces show the usual "sandstone-veinings", but the material of the veins in the highest flow on Belmakelly is a sandy limestone. They give no evidence of having undergone contemporaneous erosion. This lava series does not appear in the northern limb of the Strathmore syncline, and, like the hypersthene bearing series in the Arbuthnott group, thickens towards the south and east.

In the coarse quartzite conglomerates of this group the boulders which occur in greatest numbers are flaggy gneisses of the "Moine" type. Quartzites and vein quartz also play an important part. Jaspers and "green rocks" are much less numerous than in the lower conglomerates, although locally, on the Garvock side of the syncline, they are fairly abundant. The presence of numerous boulders of rhyolites and acid andesites shows that the acid volcanic rocks had not yet been entirely removed from the Highland area. It may be noted in this connection that the finer sediments of this group often contain a remarkable amount of felsitic debris. The chief/

chief characteristic of the conglomerates, however, is undoubtedly the great abundance of boulders of flaggy "Moine" gneisses. The flat boulders of the gneisses frequently show beautifully an imbricated arrangement similar to that found in torrential flood gravel. This is seen particularly well in the conglomerates of Sarah's Den on Strathfinella, where it is very evident that the boulders have been transported from the north or north-west.

Of the many intercalations of finer sediments two persistent belts call for special description. The first occurs between the Strathfinella conglomerates and the top of the volcanic conglomerates of the Arbuthnott group, and is separated from the latter by lenticles of "Highland" conglomerate. It consists of reddish micaceous sandstone - often pebbly, and in places containing so much felsitic debris that it assumes a pink tint - interbedded with red grey, and chocolate-coloured flagstones which are usually crowded with clay galls. Beautiful ripple-marked surfaces are often conspicuous and fine examples of sun-cracks are not uncommon. The only evidence of organic life is the presence of worm burrows and castings.

The other belt, which also occurs near the base of the group, but on the south side of the syncline, comes on almost immediately above the highest lavas of the Arbuthnott group. It includes purplish sandstones with which are intercalated grey and chocolate-coloured sandstones with olive-tinted sandy mudstones. The best section in this series occurs in the Den of Morphie about two miles east of Marykirk. Beautiful specimens of Kampecaris Forfarensis were ob-

tained/

obtained from this locality many years ago by David Page and these were afterwards described and figured by Dr Peach.* Along with my friend, Mr W.T. Gordon, I spent several days fossil-collecting in the Den. We found, in addition to fragments of myriapods, fine specimens of Parka decipiens, fragments of Pterygotus anglicus, and fragmentary fish remains which, unfortunately, are not determinable. The green mudstones are often richly charged with plant remains, including casts of ribbed stems about two inches in diameter, but so far none of the plants except Parks decipiens has been named, and probably most of the material is indeterminable. The collection of fossils from Den of Morphie in Montrose Museum includes a fish tooth and a spine of Euthacanthus.

A sandy limestone occurs near the top of the Garvock group between the North Esk and Laurencekirk. At the Bervie Water, near Pitskelly, it is represented by a calcareous sandstone with nodules of limestone which contain indeterminable plant remains. This rock has a peculiar interest in being, so far as I am aware, the only limestone in the Lower Old Red Sandstone succession in Kincardineshire. It occupies approximately the same horizon as, and is probably a continuation of, the thin limestone mapped by the geological survey in the plain of Strathmore.

(e) THE STRATHMORE GROUP. (or rather mudstones)

Here we include the well-known soft red poikilitic marls, which form the highest beds in the synclinal fold over a considerable portion of the area. Between Fettercairn and Edzell the marls pass upwards/

* Trans. Roy. Phys. Soc. Edin. 1882.

upwards into a series of conglomerates and sandstones. This group is the only one in which there is no trace of contemporaneous volcanic activity.

SUMMARY OF THE PALAEONTOLOGICAL EVIDENCE.

As will be seen from the above description of the various groups in the succession, fossils are of rare occurence in the Kincardineshire Lower Old Red Sandstone. The evidence may be summarised as follows :-

(a) Dunnottar Group : Parka sp. in the grey sandstones of Strathlethan Bay.

(b) Crawton Group : No fossils known to occur.

(c) Arbuthnott Group : Cephalaspis Lyelli in sandstone at Three Wells near Bervie. This sandstone is a short distance below the base of the hypersthene andesites and basalt series of lavas.
Plant fragments - indeterminable - in grey flagstones at Ford of Dillavaird.

(d) Garvock Group : Parka decipiens and other plant remains indet. Kampecaris Forfarensis; Pterygotus anglicus; Euthnacanthus sp., and other fish fragments indet. in the green mudstone series at Den of Morphie. This horizon is near the base of the Garvock group and only a short distance above the top of the hypersthene andesite and basalt series.

Worm/

Worm burrows and castings are abundant in the sandstone and flagstone series of Drumtochty Glen.

Plant fragments occur in the sandy limestone near the top of the group.

(e) Strathmore Group : No fossils known to occur.

The above list, it will be seen, does not offer evidence which can be of any great value for purposes of zoning or correlation. Parka occurs near the top of the volcanic series, and again almost at the base of the Lower Old Red Sandstone, and thus possesses the same wide range as in Forfarshire and Perthshire. In the south of Scotland it was collected by Mr Henderson in rocks of Upper Silurian age.

The Three Wells and Den of Morphie horizons, so far as can be judged from the distribution of the lava zones, probably occupy respectively very much the same position as the well-known fossil localities of Carmyllie and Turin Hill in the neighbouring county of Forfar. All the fossils found at Den of Morphie have been recorded from Turin Hill, while Cephalaspis Lyelli occurs at somewhat lower horizons, as for example, at Carmyllie and Newtyle.

The highest fossiliferous zone, the sandy limestone near the top of the Garvock group, contains plant fragments which suggest Psilophyton, characteristic of the highest beds in the Lower Old Red Sandstone of Forfarshire and Perthshire. But, unfortunately, none of the specimens are sufficiently well-preserved for satisfactory determination/

determination. It is hoped, however, that further search at the Pitskelly locality will yield better material.

VOLCANIC ACTIVITY IN KINCARDINESHIRE DURING THE LOWER OLD RED SANDSTONE PERIOD.

Volcanic activity, which had begun, as we have seen, in early Downtonian times, continued to be a characteristic feature in the physical history of the area until far on in the Lower Old Red Sandstone period. Evidence of prolonged, if intermittent, volcanic activity is found in the great development of lavas, tuffs, and volcanic conglomerates, which together form no inconsiderable part of the succession. The lavas include dacites, hornblende-biotite andesites, augite andesites, hypersthene andesites, hypersthene basalts, and olivine basalts, the basic types predominating. The volcanic conglomerates with their associated tuffs consist almost entirely of the débris of already consolidated hornblende and biotite andesites and rhyolites. No trace of volcanic vents has been found. The distribution of the volcanic rocks, however, suggests that the centres of eruption were situated along two lines, one of which lay north of the Highland fault, while the other is concealed under the North Sea. The former we shall call the "Highland group of volcanoes" : the latter includes at least two eruptive foci - one in the vicinity of Montrose, the other off the coast at Crawton - and these we shall designate the "Montrose centre" and the "Crawton centre".

1. THE HIGHLAND GROUP OF VOLCANOES.

The lavas which emanated from these volcanoes include the dacites/

dacites and acid andesites which extend from Temple of Fiddes to the Highland fault near Bogincabers. Two or three basic flows associated with them perhaps belong rather to the Crawton basalt group, but, since in the district where the two groups approach one another the nature of the solid geology is obscured by the great development of drift, it is difficult to obtain satisfactory field evidence. The fact that boulders of the basic lavas are absent from the associated conglomerates rather favours the supposition that the basalts came from the east or south-east. The acid andesites never appear in the coast section, and they attain their maximum development in close proximity to the Highland fault. It is not from the lavas, however, that we get the most convincing evidence as to the nature of the eruptions from the Highland centre or centres. One of the most remarkable features in the succession, from the base of the Downtonian to the top of the Arbuthnott group, is the great part played by acid tuffs and volcanic conglomerates. Wherever continuous belts of these can be traced inland they are found to thicken in the direction of the Highland fault. The constant association of their predominating rhyolite and acid andesite boulders with boulders of "Highland" rocks indicates that the material has come from the north or north-west. The extraordinary thickness of the successive volcanic conglomerates implies the removal of a thick accumulation of acid lavas from the Highland area. Throughout the whole of Downtonian and a considerable part of Lower Old Red Sandstone times there must have flourished, along the tract now occupied

by/

by the Dalradian schists and newer granites, a series of volcanoes whose chief products were rhyolite and acid andesite lavas and rhyolitic and andesitic tuffs. No vents, so far as I know, have been detected in that region, but some of the intrusive masses of quartz porphyry may possibly represent the positions of centres of eruption. It is tolerably certain that there is a genetic connection between the quartz porphyries and newer granites of the Eastern Grampians and the igneous rocks of Downtonian and Lower Old Red Sandstone age of south-eastern Kincardineshire.

(2) THE CRAWTON CENTRE.

The lavas erupted from this centre include the doleritic basalts of Tremuda Bay and the porphyritic basalts of the Crawton type. These lava groups thin off to north, south, and west from Tremuda Bay and Crawton, so that the volcanoes from which they came must have been somewhere to the east of the present coast line. I can find no evidence of tuffs belonging to this series. The acid tuffs and volcanic conglomerates, which underlie the Crawton basalts at Kinneff, have come from a centre somewhere to the north-west, and probably belong to the Highland Group of volcanoes. The lavas from the Crawton centre have undergone a considerable amount of contemporaneous erosion, but the boulders thus derived from quite an insignificant proportion in the composition of the interbedded "Highland" conglomerates - they never form volcanic conglomerates such as have been produced from the prolonged denudation of the acid lavas of the Highland group. The frequent presence of "sandstone-veining" shows that many of the flows were sub-aqueous.

(3) /

(3) THE MONTROSE CENTRE.

From this centre came the thick accumulation of hypersthene andesites, hypersthene basalts, and olivine basalts which constitute the lava content of the Arbuthnott and Garvock groups. Tuffs again are absent. No trace of contemporaneous erosion has been observed exccpt in the lowest flows in the neighbourhood of St. Cyrus. The lavas, however, almost without exception, appear to have been sub-aqueous, and present excellent opportunities for the study of "sandstone-veining", The hypersthene-bearing members of the series are remarkable for their fine development of agates. The vesicles of the olivine basalts of the Garvock group contain fine specimens of calcite, desmine, and analcite. The lavas belonging to this centre are present in great force when they appear in the southern limb of the Montrose anticline, but they gradually thin out and the intercalations of sandstone and conglomerate become thicker as they are traced to the south-west. They thin out in similar fashion in Kincardineshire as they are followed to the north-east, and, since no signs of volcanic vents are found in inland sections, one can only conjecture that the centre of eruption must be concealed to the eastward under the flow of the North Sea.

HYPABYSSAL INTRUSIONS OF LOWER OLD RED SANDSTONE AGE.

The hypabyssal intrusions include dykes of quartz porphyry, biotite porphyry, diorite porphyrite, and dolerite, and thin sills and dykes which are lamprophyric in character. Most of the lamprophyres are too small to be shown in the 1-in map; they form, however, quite /

quite a characteristic feature in the volcanic conglomerate zone underlying the Crawton basalts. As in most volcanic areas the minor intrusions belong to a late phase in the volcanic history. In Kincardineshire most of them are intruded into, and are, therefore, younger than the lower ~~pro~~portion of the Arbuthnott group; they do not cut the hypersthene andesite and basalt lavas in any of the higher members of the series.

Comparing the Kincardineshire Old Red Sandstone with a typical Scottish Carboniferous succession one is struck at once with the almost entire absence of intrusive sills. A few thin sills occur, but we find none at all comparable to the characteristic intrusions of Carboniferous age. Comparing it again with a series of Old Red Sandstone volcanics such as the Cheviot group, or the Lorne volcanic plateau, one notes the relatively poor developement of the dyke phase. The paucity of dykes and sills may reasonably be correlated with the absence of vents. It is worthy of note, too, that dykes of presumably Old Red Sandstone age show a marked increase in number in the schist area between the Highland fault and the newer granites; and, further, that the development of minor intrusions in the Old Red Sandstone area reaches its maximum at the coast line between Johnshaven and Braidon Bay. Such a distribution of the hypabyssal intrusives strengthens the suggestion that the volcanic centres were situated along ~~the~~ two lines - one in the area now occupied by the newer granites, the other to the east of the present coast line.

GENERAL PHYSICAL CONDITIONS.

The /

The Lower Old Red Sandstone of the Midland Valley of Scotland is characterised everywhere by the development of coarse conglomerates. A study of the succession in south-eastern Kincardineshire brings out very clearly two points : (1) the total thickness of coarse conglomerates is far greater than that of the finer sediments; (2) the coarseness of the average conglomerate is remarkable even for a Scottish Old Red Sandstone district. At many horizons the boulders average about two feet and frequently the magnificently rounded boulders of quartzites, granites, schistose grits, and other "Highland" rocks measure from three to seven feet along their longest diameter. It is difficult, indeed, to realise that the rounding and transportation of these boulders has been accomplished by the agency of moving water, either by waves or by mountain torrents. Not only are the blocks well-rounded, but the hard, fine-grained, homogeneous types show remarkable curved fractures, "chatter markings", which indicate in no uncertain fashion the treatment to which they were subjected before they were finally buried in the wonderful gravels of Old Red Sandstone times. The conglomerates, whether we regard them as old beaches or as stream gravels, and the finer sediments with their prevalent ripple marks and sun-cracks can only represent shallow water conditions; the association of remains of myriapods and plant debris in the latter undoubtedly indicates deposition in close proximity to a land area. The formation offers no evidence either of marine or of deep water conditions of sedimentation.

The composition of the conglomerates shows clearly that, throughout/

throughout the whole of Lower Old Red Sandstone times, the Highland area was undergoing extensive denudation. The extraordinary abundance of jaspers, cherts, and "green-rocks" in the lower conglomerates indicates that these? Upper Cambrian rocks must have extended far over the eastern Highlands - it may have been as a great recumbent synclinal fold. Again, the frequent occurrence of boulders of the "Haggis rock" must imply the former presence in the Highland area of ~~Lower~~ Silurian* rocks. The composition of the highest conglomerates with their predominating flaggy gneisses of "Moine" type suggests again an extension of these rocks far to the south and east of their present habitat. In the conglomerates of the lower two-thirds of the series one can detect frequently an alternating predominance of Upper Cambrian rocks and acid andesites, which suggests that at successive periods the supply of jasper-green-rock material was temporarily cut off by the discharge of acid lavas from the Highland group of volcanoes.

The extensive denudation of the "Highland"rocks and the consequent accumulation of the enormous thickness of Lower Old Red Sandstone sediments can only mean, as Sir Archibald Geikie has suggested, an uplift of the Highland area accompanied by a sagging of the tract now occupied by the Midland Valley. That subsidence began, as we have already noted, in Downtonian times, and, interrupted by a movement of uplift in the Pentland Hills and Lanarkshire before the deposition of the basement greywacké conglomerates of the Lower Old Red Sandstone, went on continuously along the northern tract until the close of the latter period.

Nowhere in Kincardineshire does the distribution and character of the/

* Silurian = Ordovician and Silurian.

the volcanic conglomerates suggest the destruction of volcanic islands and the consequent formation of coarse beaches. The constant association of "Highland" boulders with those of volcanic origin, and the thickening of the volcanic conglomerates when traced towards the Highland fault, point conclusively to the Highland area as the source of the material. It seems to me that all the conglomerates are old torrential gravels rather than beaches, and for two reasons; (1) The composition of the conglomerates is suggestive. In the magnificent section at Crawton, for example, the rocky foreshore coincides in position with the eroded surface of the Crawton basalt, with many of the hollows still filled with conglomerate. This uneven junction may be traced round an isolated stack which extends seawards for about twenty yards, and may be followed again in the cliff section to the north. If the overlying conglomerate were an old beach one would expect it to contain a big proportion of boulders of the lava, whereas only a very few can be seen and that in an exposure, which, as indicated above, extends over a considerable area. Indeed, in all the conglomerates the admixture of rock types brought together from widely separated areas suggests powerful torrents as the chief eroding and transporting agents. (2) The numerous storm beaches on the Kincardineshire coast have received their constituent boulders in large part "ready made" from the disintegration of the local Old Red Sandstone conglomerates, and may, therefore, well be compared with the latter. Both show a characteristic imbricated arrangement of their boulders, and since the general trend of the coast is parallel to the Highland border/

border, and, therefore, probably to the successive shore lines of the Old Red lake, we should expect the boulders of the conglomerates - if those represent beaches - to overlap in the same manner as the stones of the modern beach. Wherever the imbricated arrangement has been observed, however, in the conglomerates, it indicates that the boulders were placed in their present position relative to one another by currents coming from the north or north-west.

There can be no doubt, I think, that the accumulation of the boulders and their exquisite rounding must be ascribed mainly to the action of torrential rivers rather than to wave action along the shores of a lake. None of the beaches of the great fresh water lakes of the present day are at all comparable with the coarse conglomerates; but the latter recall at once modern torrential flood gravels and the fluvio-glacial gravels of late glacial times.

In short, the coarse conglomerates of ~~an~~ our area represent the coarse torrential gravels swept outwards from a lofty "Highland" mountain range on to the margin of a wide frontal plain, across which extended a great shallow fresh water lake or chain of lakes in which were accumulated the finer gravels, sand, and silt now consolidated to form the finer conglomerates, sandstones, and shales. To the north and west along the flanks of the mountains, and to the east beyond the limit of the present land, stretched two lines of active volcanoes. The former supplied the acid lavas and tuffs, and, indirectly, the volcanic conglomerates; from the latter were extended the basalts and basic andesites. The eastern volcanoes may have formed a chain of volcanic islands, but no evidence of that has been detected within the area with which we are concerned.

UPPER/

UPPER OLD RED SANDSTONE.

On the Kincardineshire coast at St. Cyrus there occurs a small area of Upper Old Red Sandstone. I have not yet mapped this area., and detailed description is reserved for a future paper. It may be noted, however, that the Upper Old Red Sandstone series here consists of a lower group of cornstones and calcareous sandstones, and an upper group of bright red poikilitic sandstones and marls. In the coast section at Esat Mathers, and again at Rockhall, it is faulted against the Lower Old Red Sandstone; its north-western boundary is probably also a line of faulting. The base of the series is not seen. No fossils so far as I know, have been found in this St. Cyrus outlier, but its lithological characters alone are sufficient to correlate it with the Upper Old Red Sandstone series of Arbroath, which rests unconformably on the folded and highly denuded Lower Old Red Sandstone.

THE MAIN STRUCTURAL FEATURES. Plates VI & VII figs. A, B, C & D.

Along the greater part of its course across Kincardineshire the Highland fault forms the boundary between the Downtonian - Lower Old Red Sandstone series and the older rocks to the north-west. From St. Mary's Chapel to Carron Point (see Sketch map, fig. 1) a small area of Upper Cambrian occurs on the south side; and at Kirkton in the extreme west?lavas of Old Red Sandstone age are found on the north side of the fault. In the coast section at Craigeven Bay, and again in a small stream near Elfhill - the only two localities at which the actual line of dislocation has been observed - the Highland fault is an overthrust, not a normal fault as has been supposed.

The/

The main structural feature is a continuation of the well-known synclinal fold of Strathmore, the axis of which passes out to sea near Maiden Kaim. In the area to the west of Elfhill there is a tendency to set up a steep-limbed anticline pitching out to the south-west against the Highland fault, and succeeded towards the north at Bogincabers by an inverted syncline. Plate VII C Convincing evidence of the character of the Elfhill anticline is obtained in the Water of Bervie section, where various beds in the Arbuthnott group can be traced round the fold; in the vicinity of Bogincabers a thick covering of drift obscures the solid geology, but the distribution of the hornblende andesites is strongly suggestive of the presence of an inverted synclinal fold.

An important dip fault crosses the Strathmore syncline from Thorny hive Bay to the Highland fault near Fetteresso. The southern limb of the syncline is traversed by two sets of powerful faults, trending respectively south-east and north-west, and east-north-east and west-south-west. Frequently also along the same limb - and especially in the southern part of the area - there occur "shatter belts" marked by conspicuous breccias, but along these dislocations little or no vertical displacement has been effected.

PETROGRAPHY OF THE LAVAS OF LOWER OLD RED SANDSTONE AGE.

The lavas comprise, as we have already noted, dacites, hornblende-biotite andesites, angite and hypersthene andesites, olivine-hypersthene basalts, and olivine basalts, including dolerites.

1. DACITES. (Plate II fig 1.).

Dacites occur only at one locality - along the lower slopes of the/

the Droop Hill between the Water of Bervie and East Kinmonth. They are pink in colour and weather with a pale yellowish crust. They show abundant phenocrysts of quartz, clear, glassy felspars, and biotite, embedded in a compact felsitic groundmass. The phenocrysts, and particularly the biotites, show a marked fluidal arrangement. Xenoliths of quartzite are not uncommon.

The quartz crystals nearly always show traces of crystal outlines. Sometimes, indeed, as may be seen in hand specimen, they are quite euhedral with characteristic bipyramidal terminations. Usually, however, they have undergone a considerable amount of corrosion. They contain fluid cavities, often arranged in lines, and frequently also glass enclosures and small zircons. Many of the crystals are cracked and broken, the cracks being filled with chalcedony. The felspars are mainly plagioclase; sanidine occurs in relatively small amount. The plagioclase crystals, which are usually broken and corroded, show twinning in the albite, pericline, and Carlsbad laws. Occasionally they contain glass enclosures, small zircons, and minute needles of apatite. Part of the plagioclase has a mean refractive index about the same as that of the ordinary ray of quartz, and, since the sections give low extinction angles, it must be a variety of oligoclase; many sections, however, show a higher refractive index, and in such the pairs of symmetrical extinction angles obtained in crystals showing both Carlsbad and albite twinning indicate andesine. The plagioclases are sometimes zoned. They are, as a rule, remarkably fresh, but they often show beautifully the phenomenon of albitization, which has been shown by Bailey and Grabham* to be a common feature in the/

* Geolog. Mag. 1909. p. 250.

the plagioclases of many Carboniferous basalts. In some of the slides oligoclase predominates, in others andesine Sanidine is always present, but in relatively small amount, in untwinned or simply twinned crystals. It has a refractive index well below that of balsam, and gi gives nearly straight extinction for the two halves of Carlsbad twins. The biotites are intensely pleochrioc from pale yellowish brown to deep reddish brown or almost black. They contain numerous enclosures of zircon and apatite. Many of the slides contain also fairly large c crystals of zircon.

The groundmass is almost entirely cryptocrystalline: only rarely does it show small patches which are finely microcrystalline. The cryptocrystalline material often exhibits a marked "streaky" character which probably indicates fluxion structure. It contains also in places imperfectly formed spherulites.

The abundance of the quartz phenocrysts suggest that these rocks are rhyolites, but the predominance of oligoclase and andesine in the felspar content shows that their affinities are rather with the andesites. They obviously belong to the cale-alkali series of lavas, and the large development of quartz necessitates their being placed in the acid group of that series, namely the dacites.

(2) HORNBLENDE BIOTITE ANDESITES.

Overlying the dacites come hornblende-biotite andesites, which, like the former, are restricted to one horizon. They include macroporphyritic and microporphyritic types.

(a) THE MACROPORPHYRITIC TYPE. (Plate II fig 2.)

Here I include the hornblende-biotite andesites which are ~~conspicuously~~/

conspicuously porphyritic in hand specimen. The freshest examples are dark grey in colour, and consist of a compact groundmass, in which are embedded porphyritic felspars and ~~thick~~ black patches, which, when examined with a pocket lens, are seen to show in some cases characteristic hornblende outlines; less frequently one can detect also in hand specimen scattered crystals of unaltered biotite. Xenocrysts of quartz are of frequent occurrence. The least altered specimens are obtained at the Burn of Guinea near Bogincabers.

~~PHENOCRYSTS~~ Phenocrysts.

The felspars invariably exhibit albite twinning, accompanied usually by twinning in the Carlsbad law. They are mainly andesine and acid labradorite, but in zoned crystals there is often an outer rim of oligoclase. Enclosures of groundmass are not uncommon, and occasional included pseudomorphs of bastite after hypersthene have been noted. Albitization is a constant feature, and it can often be seen in the zoned crystals that the central labradorite and andesine is largely changed to albite, while the surrounding oligoclase remains unaltered. The plagioclases in many of the slides are to a large extent calcified; in other cases they are partially chloritised, while very often limonite is developed along the cracks and cleavages.

~~HORNBLENDE AND BIOTITE.~~

After plagioclase the most abundant phenocrysts are hornblende and biotite. These always show marked evidence of resorption, and, as a rule, the process has gone so far that little or none of the original mineral is left. Its character, however, can be inferred from the/

the shapes of the areas of magnetite or of magnetite and granular augite.

Subordinate to the above are characteristic bastite pseudomorphs after hypersthene and occasional phenocyrsts of greenish angite. In most of the slides, too, there are fairly large crystals of apatite, dichoric in brownish and bluish tints. This variety of apatite has not been observed in any of the other lavas in our area. A similar dichoric apatite has been described by Dr Flett* from the andesites of the Ochils and by Mr Kynaston[2] from the andesites of the Lorne volcanic plateau. Small zircons are also accessory.

~~GROUNDMASS.~~

The groundmass is built up largely of minute straight-extinguishing laths of oligoclase often showing good fluidal structure. It contains also scattered granules of greenish angite, sometimes replaced by calcite, and minute crystals of magnetite. Not infrequently there may be seen with high powers small patches of mesostasis, which is often unresolvable and may represent original glass, while in places again, it consists of quartz containing groups of minute felspars enclosed in micropoikilitic fashion. Quartz, indeed, can be detected in the groundmass of most of the slides, but it may in part be secondary. Vesicular structure is often well developed, and the vesicles are filled with chalcedony, quartz, and chlorite.

(b) THE MICROPORPHYRITIC TYPE. Plate II fig. 3.

Here are included andesites, which, in hand specimens, appear to be non-porphyritic. They are compact, fine-grained rocks, sometimes vesicular, and exhibit a characteristic platy structure. They vary in colour/

* Trans. Edin. Geolog. Soc. Vol. VII p. 292.
2. Do. p. 402.

colour from dark grey to dark reddish brown; intermediate varieties occur in which the prevailing greyish tint is streaked with red. Their characters in hand specimen recall the Carboniferous mugearites. Some of the varieties resemble the Blackford Hill andesite, the affinity of which to the mugearites, is shown by chemical analysis, has been pointed out by Dr Flett*. But, like the Blackford Hill type, they differ from the mugearites in the absence of olivine. They are on the whole somewhat more basic than the macroporphyritic type with which they are associated, but, since they contain occasional biotites and hornblendes, or their resorption equivalents, I have included them with the above group of acid andesites. Chemical analyses would be of value in determining the true position of these interesting rocks. The freshest examples were obtained from old quarries at ~~Miniory~~ Muiry Hillock, Glenbervie.

In microscopic section they are seen to be very sparingly microporphyritic with plagioclase, biotite and hornblende, which have been almost completely resorbed, pale greenish angite, and basite replacing rhombic pyroxene. The plagioclase shows partial albitization. These small phenocrysts, however, occur only sporadically. The bulk of the rock consists of a very fine-grained, holocrystalline aggregate of small plagioclase laths, anhedral granules of pale greenish angite, with magnetite, apatite, and rarely zircon as accessories. Interstitial quartz is always present. Sections from different parts of the same flow show considerable variation in the proportions of granular angite and felspars, but the former is invariably present in greater abundance than in the groundmass of the macroporphyritic type.

This/

* Geology of neighbourhood of Edinburgh 1910. p. 34.

This perhaps may be due to the almost complete resorption of previously existing hornblende and biotite. Many of the minute plagioclases are straight-extinguishing and have refractive index about the same as that of the ordinary ray of quartz; others have higher refractive index, and crystals showing albite twinning give symmetrical extinction angles up to 22°. Hence the plagioclase may be taken to range from oligoclase to andesine. There is often good fluxional arrangement of the felspar laths. A constant feature is the presence of minute areas in which decrease in the proportion of angite is accompanied by a development of patches of quartz enclosing oligoclase laths in micropoikilitic fashion. Such areas are crowded with minute needles of apatite, and fluidal structure is absent. They probably represent a late miarolitic stage in the process of consolidation. No glassy base has been detected, but, when examined with high powers, some of the slides show a small amount of interstitial badly differentiated? felspars. The character of the microscopic sections of the "reddened" varieties is very much obscured by the development of secondary iron oxides, mainly limonite. These oxides also occur in large, irregular patches in the grey varieties. The vesicles are filled with chlorite and calcite.

(3) ANGITE ANDESITES. Plate II fig. 4.

Angite andesites are found at Carmont Hill and Strathlethan Bay. The Strathlethan Bay variety is a reddish brown rock conspicuously porphyritic with felspars and with areas of a green chloritic substance evidently replacing one or more ferromaguesian minerals. In microscopic/

microscopic section the phenocrysts are seen to consist mainly of plagioclase and pryoxenes. The most abundant are the plagioclases in large corroded crystals which exhibit Carlsbad, albite, and pericline twinning. Conjugate extinctions in sections of Carlsbad-albite twins indicate acid and medium labradorite. The commonest alteration in the felspar is the formation of albite, and every degree of transition is found from fresh clear labradorite with only very slight development of albite to crystals which are completely albitized. The original character of the latter cannot of course be determined, but it is fairly certain that originally all the plagioclase phenocrysts belonged to acid and medium labradorite. Enclosed in the felspars are occasional small idiomorphic pseudomorphs of bastite after rhombic pyroxene. The abundant ferromagnesian phenocrysts include both monoclinic and rhombic pyroxenes in rather small idiomorphic crystals, with the former predominating. The augite is occasionally fresh, but is in great part replaced by calcite and chlorite; the rhombic pyroxene has undergone complete alteration to bastite. Occurring sporadically in the sections are small heaps of granular magnetite, which suggest the former presence in small amount of hornblende or biotite. In a few cases a little biotite remains, but, as a rule, resorption has been so complete that only irregular areas of magnetite remain to tell the tale.

The character of the groundmass is somewhat obscured by weathering, but it consists mainly of closely packed microlites and minute laths of felspar, the latter sometimes showing multiple twinning. From the low extinction angles of the plagioclase laths one may infer that they belong to oligoclase and oligoclase-andesine. Secondary iron/

iron oxides probably represent original granules of angite. A few small zircons are also present; and there is a little interstitial quartz which may be secondary.

The Carmont Hill flow belongs to a somewhat more basic type. Dark red in colour, and veined with red chalcedony, it is conspicuously porphyritic with angite and felspar, and in places is vesicular. In microscopic section it is characterised by the abundance of its phenocrysts of dark green angite, the crystals of which are sometimes sharply euhedral, sometimes much corroded. Rhombic pyroxenes are absent. With the exception of small scattered crystals of magnetite the only other phenocrysts are the felspars, which are strongly zoned plagioclases, consisting mainly of medium labradorite. These are much corroded, exhibit Carlsbad, albite, and pericline twinning, and contain glass enclosures and crystals of augite. The groundmass is hyalopilitic, consisting of rather stout laths of plagioclase with forked terminations, and often showing multiple twinning, with a small proportion of anhedral granules of green angite, embedded in a brown glassy base. The felspar laths give fairly high extinction angles, and are probably mainly andesine and acid labradorite. The numerous vesicles are filled with chlorite.

(4) HYPERSTHENE ANDESITES AND HYPERSTHENE BASALTS.

The most extensive lava horizon in our area, that which occurs near the top of the Arbuthnott group, is characterised by a great development of basic hypersthene-bearing rocks. It includes hypersthene andesites, ~~hypersthene-olivine andesites~~, hypersthene basalts, and olivine basalts. Hornblende has not been found, but otherwise this/

this group resembles closely the hypersthene-bearing series of the St. Vincent lavas described by Dr Flett*. At one end of the series are normal hypersthene andesites without olivine, at the other typical olivine basalts with little or no hypersthene. Between these extremes are found numerous transition types with varying proportions of hypersthene and olivine. The andesitic varieties predominate in the northern part of the area, the basalts attain their greatest development towards the south. Owing to the drift-covered character of the country, and to the abundance of transition types, it has not been found possible to separate the different varieties on the map. One colour has been used to indicate the position of the hypersthene-bearing basic series as a whole. The olivine in all the above types is replaced by iddingsite. At the base of the group, and intercalated at a few higher horizons in the western part of the area, there occur normal olivine basalts without hypersthene, and in these the olivine presents the usual alteration to serpentine and carbonates.

(a) HYPERSTHENE ANDESITES.

Many of these, particularly the hyalopilitic types, are remarkably fresh. They are deep black in colour, with a velvety lustre, and are traversed in every direction by thin veins and veinlets of red chalcedony. Such examples recall at once the well-known hypersthene andesite of Dumyat, described by Dr Flett[2]. Others again possess a greyish black tint, while many, especially the more crystalline varieties, have the "reddened" appearance, which is so characteristic of basic Old Red Sandstone andesites, generally. All are conspicuously porphyritic/

* Phil. Trans. Roy. Soc. Series A. Vol. 208. p. 305.
2. Trans. Edin. Geolog. Soc. Vol. VII p. 290

porphyritic with glassy felspars and black pyroxenes, while in hand specimen the groundmass is seen to be sometimes compact and lithoidal, sometimes distinctly crystalline.

The minerals of the first generation include plagioclase, hypersthene, and augite. Magnetite and apatite are constant accessories. The plagioclases occur in elongated, tabular crystals, sometimes sharply euhedral, more often somewhat corroded. They are remarkably fresh except for the occasional development of limonite along the cracks and cleavages, and are usually quite free from enclosures, although now and again one meets with crystals honeycombed with glass cavities. Albite twinning is found in nearly every crystal, and is associated very often with twinning on the Carlsbad law. Pericline twinning occurs less frequently. Many of the crystals are strongly zoned. From the abundance and fresh condition of the plagioclases it was easy to obtain large numbers of sections suitable for measurement of extinction angles. Conjugate extinctions in sections of Carlsbad-albite twins showed that the predominating variety is medium labradorite. The core of some of the zoned crystals is somewhat more basic; the marginal zones of many sections gave angles which indicated acid labradorite. The pyroxenes include both hypersthene and augite in varying proportions, but with the former usually predominating. The hypersthene is remarkably fresh, showing only occasionally slight alteration to bastite. It shows the usual dichroism. Its double refraction is weak, and this character, as Dr Flett has pointed out, enables one to tell at a glance the relative proportion of rhombic and monoclinic/

monoclinic pyroxenes in a slide. The augite is pale brown in colour and is not dichroic. Twinning in the orthopinacoid is of frequent occurrence. Some of the phenocrysts show graphic intergrowth of monoclinic and rhombic pyroxenes. Glomeroporphyritic groups of angite, hypersthene, and plagioclase occur quite frequently. Plate II fig. 6.

Perhaps the commonest type of groundmass is the hyalopilitic with plagioclase laths, anhedral granules of augite, and magnetite embedded in a brown glass. The lath-shaped felspars show a rude fluxion structure. They often exhibit multiple twinning and consist chiefly of andesine and acid labradorite. The augites of the second generation are crowded with minute grains of magnetite. The orbicular structure described by Dr Flett in the Dumyat rock has not been observed. With increasing size of the felspars and angites of the groundmass, accompanied by decreasing amount of glassy base, we get a transition through intersertal types, to types which are almost holocrystalline. The exceptional variety in Paldy Fair Den, Plate II fig. 5. already mentioned as being remarkable for the abundance of ~~the~~ xenoliths, must have been originally a vitreous, vesicular type. The glassy base is now represented by a lithoidal cryptocrystalline substance, which is in part so fine as to be unresolvable even with high powers, but in places can be seen to be crowded with minute microlites of felspar, ? angite, and magnetite. The rock closely resembles a hypersthene andesite bomb from Wallibu, St. Vincent, described and figured by Dr Flett.* The steam cavities are filled with chalcedony. Opal is of frequent occurrence as a secondary, or perhaps rather "pneumatolytic" mineral; and, as we have seen, the hypersthene andesites carry fine specimens of agate.

Varieties/ * Phil. Trans. Roy. Soc. Ser. A. Vol. 208. Pl. XXVI fig 4.

Varieties of hypersthene andesite with increasing amount of accessory olivine give an easy transition to our next group, the hypersthene basalts.

(b) HYPERSTHENE BASALTS. *Plate III fig. 1.*

Many of these are holocrystalline, and in all the other cases the glassy base forms, relatively, a very small proportion of the groundmass which tends to be rather coarsely crystalline. The phenocrysts include plagioclase, olivine, hypersthene, and augite. The olivine, which has evidently undergone intense corrosion, rarely if ever shows crystal outlines, and is always completely replaced by iddingsite. The corrosion borders of hypersthene described by Dr Flett in the St. Vincent rocks have not been observed. As a rule olivine is very much in excess of hypersthene and augite. The plagioclases are always the most abundant of the porphyritic constituents and are strongly zoned labradorites. Labradorites and augite are repeated in a second generation, and, in the holocrystalline varieties, there is a tendency for those two minerals to crystallise in sub-ophitic intergrowth. Apatite and iron oxides are common accessories.

(5) OLIVINE BASALTS.

Basalts without hypersthene occur in all the lava zones from the Tremuda Bay zone upwards. They consist of plagioclase, augite, and olivine, with apatite and iron oxides as constant accessories. Structurally they include two well-marked groups :-

(A) Coarsely crystalline doleritic types.

(B) Compact basaltic types, which may be holocrystalline or hypocrystalline/

hypocrystalline.

Further sub-division is rendered difficult by the occurrence of varieties which are intermediate in character between well-marked recurrent types.

(A) THE DOLERITIC TYPES.

Two main types may be recognised here - non-porphyritic and porphyritic.

(a) NON-PORPHYRITIC DOLERITES. *Plate III figs. 3, 4 + 5.*

These have a wide distribution. They occur in the Dunnottar group at Tremuda Bay, in the Crawton group at the Pitkerty Burn, in the Arbuthnott group among the lavas at Johnshaven low down in the group, and again as intercalated flows in the hypersthene-bearing series at Ecclesgreig, and finally they form the predominating type in the Garvock group. The olivine is completely replaced by serpentine, limonite, haematite, and carbonates, but frequently shows characteristic outlines. The augite, which varies in colour from pale brown to the purplish brown tint, which is taken to indicate richness in titanium, occurs in large irregular plates which invariably show ophitic intergrowth with the plagioclases. Between the ophitic patches the plagioclase appears in broad laths grouped with a rude fluidal arrangement, Those large felspars are strongly zoned, the basic core being often somewhat decomposed. Extinction angles for successive zones indicate basic to acid labradorite. The augite is sometimes partially replaced by chlorite and calcite, and along with this change may be noted partial chloritisation of the felspars. Apatite is abundant in long thin/

thin needles. Very rarely there are scattered patches of intersertal mesostasis.

The fresh rock is black, but the usual tint of the specimens is a dark brownish red. The coarsely-crystalline, non-porphyritic character is obvious in hand specimens. Many of the flows are markedly vesicular, and the vesicles contain calcite and heulandite, with which are associated at Garvock fine crystals of analcite and desmine.

(b) PORPHYRITIC DOLERITES.

Porphyritic dolerites occur mainly at the base of the hypersthene andesite and basalt zone. Good examples appear near Druidsdale, on the Bervie Water south of Arbuthnott church, and again in the Peattie Burn ¼ mile east of Kow Ford. They differ from the above group only in the presence of porphyritic labradorite and olivine.

(B) COMPACT BASALTIC TYPES.

(a) THE CRAWTON TYPE. Plate IV fig. 1.

This rock at once recalls the well-known Carnethy "porphyry"* of the Pentland Hills. Varying in colour from grey to dark reddish brown according to its state of preservation, it may be distinguished from all the other lavas of the area by means of its characterised, large, tabular, euhedral felspars. These sometimes occur sporadically; more frequently they are so numerous and arranged so closely together along what have been lines of flow, that they impart to the rock a pronounced platy character.

In microscopic section it is seen that the chief constituent of the rock is plagioclase felspar. The large tabular plagioclases are/

* Geology of Neighbourhood of Edinburgh 1910. p. 32.

are twinned on the albite, Carlsbad, and pericline laws. They show little trace of decomposition. Occasionally they enclose serpentinised olivines. Conjugate extinctions in Carlsbad-albite twins indicate medium to basic labradorite. As a rule the only other porphyritic constituent is olivine, which occurs in rather small, much corroded crystals, and is completely replaced by serpentine, limonite, and carbonates. In one or two cases the outlines of calcite areas are suggestive of augite, but no fresh porphyritic augite has been observed in any of the slides.

The groundmass is holocrystalline, consisting of labradorite and olivine in a second generation of crystals, along with anhedral granules of augite, often partially replaced by chlorite and calcite. Apatite, in long thin needles, and iron oxides are also abundant as accessories.

(b) OTHER HOLOCRYSTALLINE PORPHYRITIC BASALTS.

This group includes a somewhat varied assemblage of types, which agree in having a holocrystalline groundmass consisting of labradorite, augite, and magnetite, but which show considerable variation in the character of their porphyritic constituents.

From Banff Hill to Barras the hypersthene basalts are succeeded by olivine basalts which are closely related to the former, and, indeed may be considered as extreme members of the hypersthene andesite - hypersthene basalt series, in which olivine entirely supercedes hypersthene. In the vicinity of Barras they contain phenocrysts of iddingsite and labradorite in a groundmass similar to that of the holocrystalline/

holocrystalline hypersthene basalts. From Hillhead of Arbuthnott southwards as far as Banff Hill they are compact reddish grey rocks, with platy jointing, and the only phenocrysts are abundant olivines replaced by iddingsite. Plate III fig. 2. Intercalated with the hypersthene andesites above Benholm Bridge there is a compact basalt sparingly porphyritic with plagioclase and serpentine pseudomorphs after olivine.

Overlying the Crawton type at Wardend, Kinneff, and at Crawton there is a zone of fine-grained basalts sparingly porphyritic with small phenocrysts of olivine and angite. The groundmass of these basalts is particularly rich in angite, and olivine also occurs in a second generation of crystals. At the Glaslaw Burn a flow on approximately the same horizon differs from the above only in having fairly numerous phenocrysts of labradorite. Plate IV fig. 2.

Associated with the doleritic lavas in the Garvock group there are basalts in which abundant phenocrysts of olivine (completely altered to serpentine and iron oxides) and labradorite are embedded in a groundmass consisting of large felspars laths the interstices between which are crowded with minute granules of angite and magnetite.

(c) HOLOCRYSTALLINE NON-PORPHYRITIC BASALTS. Plate III fig. 6.

Underlying the Crawton type at Bervie Brow, and immediately overlying a flow of the same type at Whistleberry wood occur holocrystalline even-grained non-porphyritic basalts, exceptionally rich in olivine. Their angite and plagioclase show sub-ophitic intergrowth.

(d) HYPOCRYSTALLINE BASALTS.

Included here are basalts in which the groundmass contains a considerable/

considerable proportion of glassy base. They are usually porphyritic - sometimes with olivine alone, as at Woodstone Den, St. Cyrus; sometimes with olivine and plagioclase, as at Den of Morphie; less frequently with olivine, plagioclase, and angite as in a flow ¼ mile east of Forth Hill quarry. The glass may occur in intersertal patches or be distributed evenly throughout the groundmass.

An exceptional type occurs in association with the acid andesite group at Hawkhill on the Water of Bervie and again in the Pilkettty Burn. It is a heavy, compact, black rock, not conspicuously porphyritic in hand specimen. In thin section it is seen to contain abundant phenocrysts of olivine, sometimes euhedral, but often corroded and penetrated by tongues of groundmass. The olivines are to a large extent serpentinised, but occasionally there are left in the centre of the crystals small patches of fresh olivine. This is the only occurrence of unaltered olivine which I have observed in these Old Red Sandstone lavas. The groundmass consists mainly of clear lath-shaped plagioclases, showing fluidal arrangement, and glassy base in about equal proportions along with a second generation of olivine crystals and granular augite in relatively very small amount. The glass is crowded with dark coloured rod-shaped microlites, which have high double refraction and are probably augite. The plagioclase laths often show multiple twinning, their extinction angles indicate medium labradorite. Plate IV fig. 3.

HYPABYSSAL INTRUSIVE ROCKS OF LOWER OLD RED SANDSTONE AGE.

Here are included granite porphyries, diorite porphyrites, lamprophyres/

lamprophyres, and dolerites.

(a) GRANITE PORPHYRIES. Plate V figs. 1 & 2.

The granite porphyries include two well-marked types - quartz porphyry with abundant and conspicuous phenocrysts of quartz, and biotite porphyry in which the quartz is confined to the groundmass. Quartz porphyry dykes are found at Cowie, at Clochnahill, at Allardice Castle, and on the shore near Hallgreen Castle. They vary in colour from brownish red to brick red, and are always conspicuously porphyritic. There are slight differences in the relative abundance of the various phenocrysts, but on the whole these rocks maintain a uniform character in composition and structure. The porphyritic constituents consist of quartz, orthoclase, plagioclase, and biotite. Quartz occurs in much corroded crystals, which often contain fluid cavities arranged in lines. Orthoclase in untwinned or simply twinned crystals is often beautifully fresh, and encloses biotite and corroded plagioclases. The plagioclase is mainly oligoclase giving straight extinction and having refractive index the same as that of the ordinary ray of quartz. A few sections with slightly higher refractive index give extinctions which indicate oligoclase-andesine. The plagioclases are twinned on the albite, Carlsbad, and pericline laws. They contain abundant enclosures of apatite needles. They are often much decomposed, and show frequently partial albitization. Biotite is pleochroic in pale yellow and brownish tints; it is often partly changed to chlorite; enclosures of zircon and apatite are abundant. In addition to the above the quartz porphyries contain fairly large scattered crystals of zircon, apatite, magnetite, and sphene.

The/

The groundmass is microcrystalline, consisting mainly of turbid felspar, with quartz, and biotite also in fair amount in a second generation of crystals. In palces there is a developament of spherulitic structure, the groundmass of one slide being made up in large part of closely packed spherulites in the interstices between which lie stout orthoclase prisms and interstitial quartz. Only rarely have I noticed typical micropoikilitic structure. In the marginal portions of the dykes the groundmass is cryptocrystalline.

Plate V fig. 2.

Biotite porphyries occur in a group of dykes which appear at intervals along a line extending from the Carron Water near Mill of Forest by the Hill of Seabeg and Fawsyde, Kinneff to the coast at the Pintil stone. The most abundant phenocrysts are felspar and biotite. Very rarely a small, much corroded quartz may be noted, and the shapes of certain areas of secondary magnetite and chlorite suggest the former presence of hornblende. The biotite is of the same type as in the quartz porphyries. Large crystals of clear, unweathered orthoclase occur sporadically. The predominating felspar is albite. The mode of occurrence of the albite in amny instances suggests that it is replacing a calcic felspar. The albitization, however, is so far advanced that it has not been found possible to determine the character of the original felspar. But while much of the albite is secondary - or perhaps rather juvenile - there remains a considerable proportion which may quite possibly be primary. Frequently the felspar phenocrysts consist of a core of albite with a broad rim of orthoclase.

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up mainly of fine micropegmatitic intergrowths of quartz and felspar, with considerable variation in the type of intergrowth even within the limits of one microscopic section. With low powers the most noticeable feature is a fine development of apparent micropoikilitic structure, small irregular areas of quartz enclosing stout prismatic crystals of felspar. In places, again, spherulitic structures predominate. Many of the apparently micropoikilitic groups, however, when examined with high powers, are seen to consist of a very fine graphic intergrowth of quartz and felspar (cryptographic) showing a well marked radiating arrangement round the laths of felspar. True micropoikilitic structure is found in the interstices between those radiating groups and between the spherulites. Biotite occurs in fair amount in the groundmass.

At Clatterin' Brigs and near Kirkton occur two small intrusions noted in the geological survey maps as ~~occurring in the type rock at~~ "Lintrathen porphyry". They contain the peculiar biotite which has been described by Teall as occurring in the type rock at Lintrathen*, but the Kincardineshire examples do not carry any white mica.

(e) DIORITE PORPHYRITES.

I have included in this group a number of narrow dykes which are found in the shore section between Bervie and Johnshaven. They are pale brownish red rocks, conspicuously porphyritic with thin reddened felspars which are penetrated by the groundmass. They are sparingly vesicular, and the vesicles are filled with quartz and calcite. Small patches of "chlorite" apparently represent some ferromagnesian mineral. In microscopic section they are seen to be too much decomposed for satisfactory determination. The porphyritic felspars are oligoclase/

* British Petrography p. 286.

oligoclase and oligoclase-andesine. Areas of chlorite or chlorite and magnetite evidently replace a ferromagnesian mineral, but neither the shape nor the structure of the pseudomorphs offer satisfactory evidence as to the character of the original mineral. The groundmass consists of a plexus of elongated narrow laths of oligoclase, along with occasional short, broad prisms of simply twinned orthoclase and skeletal growths of iron oxides. A little interstitial quartz is found, but it is probably secondary.

The "Diorite" of the geological survey map which occurs in small intrusions in the vicinity of Whistleberry and Shieldhill is a type which is not easy to classify. It has affinities with the augite andesites and with the diorite porphyrites. As a rule it is not porphyritic, consisting of an even-grained holocrystalline aggregate of plagioclase, mainly oligoclase, pale purplish augite, and titaniferous iron oxide. The augite is in ragged plates often in ophitic relation to the felspars.

LAMPROPHYRES.

Numerous thin sills and narrow dykes which are intruded into the volcanic conglomerate and tuff zone between Bervie and Todhead are perhaps lamporphyres and were mapped as such. They are so highly decomposed, however, that thin sections throw little light on their original characters. The resemble the thin lamprophyric dykes of the Pentland* Old Red Sandstone volcanic series.

DOLERITES.

A basic intrusion which behaves, sometimes as a sill, sometimes as a dyke, extends from the north side of Cadden Castle to Shieldhill and/

* Geology of neighbourhood of Edinburgh 1910 p. 27.

and, shifted by the Whistleberry fault, again appears in the neighbourhood of Crowhillock. It is a typical olivine dolerite, consisting essentially of labradorite, purple augite, and abundant olivine replaced by serpentine and iron oxides. Accessory minerals include large skeletal growths of ilmenite and titaniferous magnetite and thin needles of apatite. It shows good ophitic structure.

A similar intrusion is found on the north limb of the syncline between Fallside and Clochmahill.

From the above descriptions it will be seen that the eruptive rocks of Old Red Sandstone age in Kincardineshire, as elsewhere in Scotland, belong to a normal "Pacific facies."

Intrusions later than the Old Red Sandstone Period.

Included here are two groups of intrusive rocks :- (a) a series of dolerite dykes which are of the same type, and have probably been intruded at the same time as the late Carboniferous east and west dykes of central Scotland; (b) a series of olivine analcite dolerites whose affinities are with the Carboniferous teschenites rather than with the Lower Old Red Sandstone volcanics.

(a) QUARTZ DOLERITES. Plate V, 3, 4, 5 & 6.

As will be seen from the accompanying map the quartz dolerite dykes maintain a general east-north-east and west-south-west trend. They are coarse-grained in the centre and become fine-grained and porphyritic at the margin. Their chief constituents are invariably plagioclase, augite, and large skeletal growths of titaniferous iron oxide. The augite is pale brown in colour, and occurs usually in large /

large irregular plates showing typical ophitic structure; less frequently the crystals are in part euhedral. A fine basal lamination is to be seen occasionally. The usual alteration product is chlorite or calcite, but in a few cases it is found to be a green pleochroic mica. Rhombic pyroxenes have not been observed. The plagioclase is on the whole very fresh, although slightly chloritised in places. The crystals are often strongly zoned and consist of labradorite - acid to basic. Micrographic quartz has not been detected, but a fair amount of quartz occurs in the interstitial patches of mesostasis and some of it doubtless is primary. Apatite in long thin needles is a constant accessory. Olivine, always completely changed to serpentine, iron oxides, and carbonates, occurs in abundance as phenocrysts in the marginal portions of the dykes, but is found only rarely in the main mass of the rock. Intersertal patches of mesostasis are of fairly frequent occurrence, and, in the freshest specimens, consist of hollow and skeletal felspar microlites, skeletal growths of iron oxides, skeletal augite microlites, and irregular areas of quartz, in an unresolvable greenish base. The skeletal angites and the wisp-like plagioclase microlites are often seen to be in optical continuity with the adjacent large angite and plagioclase crystals. The marginal portions of the dykes carry porphyritic plagioclase, augite or augite-plagioclase ophitic intergrowths, and altered olivine; the fine-grained groundmass consists of minute laths and brush-shaped microlites of felspar, granules of calcite (probably representing angite), and small granules of iron oxide. In Kincardineshire /

Kincardineshire, as elsewhere, these dykes show beautiful ocellar structure. As was first shown by Dr Teall* these ocelli represent rounded steam cavities which have been filled with magma. The plagioclase laths and prismatic augites of the rock are arranged tangentially round areas of finely crystalline material consisting of radiating brush-shaped felspars, reticulate skeletons of iron oxide, and granules of augite. The infiltrated material closely resembles the patches of intersertal mesostasis. A particularly good example of ocellar structure is shown in Pl. IV, fig. 6 photographed from a specimen obtained from the Johnshaven dyke. It is interesting to note, too, that the quartz dolerites are frequently traversed by thin red veins, which in composition are somewhat similar to the ocelli. These veins occur at or near the margins of the dykes and evidently represent residual magma injected into a portion of the dyke which had already consolidated.

(b) OLIVINE ANALCITE DOLERITES.

A serpentine intrusion is shown on the geological survey map on the south shore of Bervie Bay. The field evidence shows that it has been intruded in the form of a sill. The lower portion is fine-grained and conspicuously porphyritic with large felspars, and passes upwards into a very basic coarsely crystalline rock which is highly altered. The top of the intrusion is concealed under the 25 foot beach. The "serpentine" is a decomposed dolerite. Although it has undergone intense alteration it is seen in microscopic section to consist of a coarsely crystalline aggregate of basic plagioclase, purple augite, and serpentinised olivine with iron oxides and apatite as accessory /

* Geolog. Mag. 1889. p. 481.

accessory minerals: it shows typical ophitic structure. The lower part of the sill is a finer grained dolerite with abundant phenocrysts of plagioclase. The latter consist mainly of medium labradorite, but usually have a broad outer zone of orthoclase. They enclose small green serpentinised olivines and occasionally crystals of purple augite. The large phenocrysts lie in a holocrystalline ground mass made up chiefly of lath-shaped felspars, purple augite, serpentinised olivines, and titaniferous iron oxides. The augite is partly euhedral, partly in irregular plates showing ophitic intergrowth with the plagioclase. The plagioclases frequently show an outer zone of orthoclase, which also occurs in separate simply twinned crystals. The orthoclase - rich parts of the rock are found associated with interstitial patches of clear analcite, showing its characteristic cubic cleavage. These areas are crowded with apatite needles. Much analcite occurs also as veins in the plagioclase. Occasionally calcite and vermicular chlorite accompany the analcite. The rock is thus an olivine analcite dolerite, and recalls the Carboniferous teschenites of the central valley of Scotland.

A further point of resemblance to the teschenites is seen in the abundant development of "segregation" veins. These consist almost entirely of orthoclase felspar, the only other constituents being scattered ragged crystals of pale green augite, skeletal growths of iron oxides, and very rarely patches of serpentine which probably replace olivine. Analcite has not been observed. The veins do not show chilled edges, and, therefore, must have been injected after the main mass of the rock had consolidated but was still hot.

Between /

Between the above sill and Horse Crook Bay two lavas are shown on the geological survey map. It is clear, however, from the way in which they transgress the sediments that they are really intrusive sheets. They are dolerites of the same type as the porphyritic portion of the Bervie Bay intrusion.

These alkali-rich intrusives in all probability have been derived from the alkali-rich magma which characterised the Midland Valley in Carboniferous times. Their affinities are with an "Atlantic" series, rather than with the "Pacific" or calcalkali series, to which the igneous rocks of the Lower Old Red Sandstone so obviously belong.

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In conclusion I wish to acknowledge my indebtedness to those who have assisted me in this work - to Professor James Geikie, L.L.D. D.C.L., F.R.S., for constant encouragement and advice during the progress of the research; to Dr B. N. Peach, F.R.S., who determined for me the specimens of the Arthropoda, and who on several occasions visited important sections and gave me valuable assistance in the field work; to Dr R. H. Traquair, F.R.S., who very kindly named most of the fishes; and to Dr John Horne, F.R.S., through whose interest and kindness the services of Mr D. Tait were obtained in order that a thorough examination might be made of the fossiliferous beds at Craigeven Bay. My friend and colleague Mr W. T. Gordon, M.A., B.Sc. gave me invaluable aid in the collection of fossils from the Downtonian series at Cowie. Dr Peach and Dr Traquair have very kindly undertaken the description of the new species of Arthropoda and fishes.

EXPLANATION OF PLATES.

PLATE I.

Figs. 1 & 2. Photographs of unconformable junction between Downtonian (D) and ? Upper Cambrian (C) at north side of Ruthery Head. The heavy white line in fig. 1 shows the position of the unconformable junction; the broken white line marks the course of one of the many small faults which tend to mask the unconformity; the fine white lines indicate planes of bedding.

Figs. 3 & 4. Photographs showing general view of above unconformity as seen on the foreshore north of Ruthery Head.

PLATE II.

Fig. 1. Dacite. Left bank of Water of Bervie near Burn of Guinea farm.

Phenocrysts of quartz, plagioclase, sanidine, and biotite in a felsitic groundmass. The photograph shows the fluidal arrangement of the phenocrysts, and in particular of the biotites. Fluxion structure is also seen in the groundmass.

x 13 : ordinary light.

Fig. 2. Hornblende - biotite andesite. North side of road at Boyincabers.

Phenocrysts of andesine (partially albitized) and hornblende, almost completely resorbed, in a microcrystalline groundmass.

x 14 : ordinary light.

Fig. /

Fig. 3. Andesite. Muiry Hillock, Glenbervie.

Fine-grained, holocrystalline aggregate of small plagioclase laths, granules of pale green augite, and magnetite with secondary limonite. The photograph shows also a patch of secondary iron oxides.

x 14 : ordinary light.

Fig. 4. Augite andesite. Carlin Craig, Strathlethan Bay.

Phenocrysts of plagioclase, partially albitized, augite replaced by chlorite, rhombic pyroxene replaced by bastite, and iron oxides secondary after ? biotite in a finely crystalline groundmass of plagioclase laths, granular augite, and iron oxides.

x 14 : ordinary light.

Fig. 5. Hypersthene andesite. Paldy Fair Den, Glenfarquhar.

Phenocrysts of plagioclase in a vesicular, cryptocrystalline groundmass. The vesicles are filled with chalcedony.

x 14 : ordinary light.

Fig. 6. Hypersthene andesite. Paldy Fair Den, Glenfarquhar.

Phenocrysts of plagioclase, hypersthene, and augite in a hyalopilitic groundmass.

x 14 : ordinary light.

PLATE III.

Fig. 1. Hypersthene basalt. Near Little Barras.

Phenocrysts of plagioclase, hypersthene, augite, and iddingsite /

iddingsite (replacing olivine) in a hypocrystalline groundmass consisting mainly of plagioclase and augite with a considerable amount of interstitial glassy base.

x 14 : ordinary light.

Fig. 2. Basalt. Hillhead Quarry, Arbuthnott.

Phenocrysts of olivine, replaced by iddingsite and serpentine, in a fine-grained holocrystalline groundmass of augite , plagioclase, and iron oxides.

x 14 : ordinary light.

Fig. 3. Doleritic Basalt. Tremuda Bay.

Holocrystalline aggregate of augite and plagioclase showing well marked ophitic structure, along with olivine replaced by serpentine, carbonates, and iron oxides. The photograph shows one exceptionally large olivine, but the rock as a whole is non-porphyritic.

x 14 : ordinary light.

Fig. 4. Doleritic Basalt. On shore between East Mathers and Johnshaven.

Holocrystalline aggregate of augite, plagioclase, olivine, and iron oxides. The augite is partly ophitic, partly idiomorphic. The olivine is replaced by decomposition products - chiefly iron oxides and green serpentine. A large serpentinised olivine near the centre of the photograph shows characteristic crystal outlines.

x 14 : ordinary light.

Fig. /

Fig. 5. Doleritic Basalt. Garvock.

Holocrystalline aggregate of plagioclase, augite, olivine, and iron oxides.

x 14 : ordinary light.

Fig. 6. Basalt. Whistleberry Wood.

Holocrystalline even-grained aggregate of olivine, augite, plagioclase, and iron oxides. This rock is exceptionally rich in olivine.

x 14 : ordinary light.

PLATE IV.

Fig. 1. Basalt of Crawton type. Whistleberry Wood.

Large tabular phenocrysts of plagioclase in a holocrystalline groundmass of plagioclase, augite, serpentinised olivine, and iron oxides.

x 14 : ordinary light.

Fig. 2. Basalt. Glaslaw Burn.

Phenocrysts of plagioclase, olivine, and augite in a holocrystalline groundmass of plagioclase, augite, and iron oxides.

x 14 : ordinary light.

Fig. 3. Basalt. Left bank of Water of Bervie, near Hawkhill.

Phenocrysts of olivine, partly serpentinised, in a hypocrystalline groundmass. The groundmass consists mainly of lath-shaped plagioclases and glassy base in nearly equal proportions : granular augite and olivine occur sparingly.

x 14 : ordinary light.

Fig. /

Fig. 4. Tuff. Shore near Cowie Harbour.

The photograph shows the angular character of the constituent fragments of acid andesites and felsites.

x 14 : ordinary light.

Fig. 5. Hornblende andesite. Boulder of predominating type in the volcanic conglomerate at Cowie.

Phenocrysts of hornblende, biotite, and plagioclase in a microcrystalline groundmass.

x 14 : ordinary light.

PLATE V.

Fig. 1. Quartz porphyry. Near ~~Alexandria~~ Allardice Castle, Bervie.

The photograph shows phenocrysts of corroded quartz, oligoclase, and biotite in a microcrystalline groundmass of quartz, turbid felspar, and biotite.

x 14 : ordinary light.

Fig. 2. Biotite porphyry. Carron Water, west of Mill of Forest.

Phenocrysts of albite, orthoclase, and biotite in a fine-grained groundmass consisting mainly of micropegmatitic intergrowths of quartz and felspar.

x 14 : ordinary light.

Fig. 3. Quartz dolerite. Rectory Quarry, Drumtochty.

The photograph shows the porphyritic character of the marginal portions of the quartz dolerite dykes. The phenocrysts include olivine replaced by serpentine, plagioclase, and augite.

The /

The small circular areas represent vesicles infilled with quartz and chlorite.

x 13 : ordinary light.

Fig. 4. Quartz dolerite. Rectory Quarry, Drumtochty.

The photograph shows two rounded steam cavities filled with infiltrated magma, which has crystallised as radiating brush-shaped felspars, reticulate skeletons of iron oxide, and granules of augite. Around the cavities the felspars of the rock are arranged tangentially.

x 14 : ordinary light.

Fig. 5. Quartz dolerite. Shore, near Johnshaven Harbour.

Marginal portion of dyke crowded with ocelli of same type as in fig. 4.

x 13 : ordinary light.

Fig. 6. Quartz dolerite. Balnakettle Burn, Fettercairn.

The photograph shows the normal character of the coarse-grained central portions of these dykes - a holocrystalline aggregate of plagioclase, augite, and iron oxides with a little interstitial quartz.

x 14 : ordinary light.

Fig. 7. Olivine analcite dolerite. Shore at south side of Bervie Bay.

The rock contains large porphyritic plagioclases in a coarsely crystalline matrix of lath-shaped plagioclase (often with /

with marginal orthoclase), purple augite, serpentinised olivine, and titaniferous iron oxide; the clear patches in the centre are analcite.

x 14 : ordinary light.

Plates VI + VII

Horizontal sections on true scale. The sections are taken in succession from north to south and illustrate the main structural features of the area.

Scale. Section A. 24 inches to 1 mile.

Sections B, C, and D. 1 inch to 1 mile.

1.

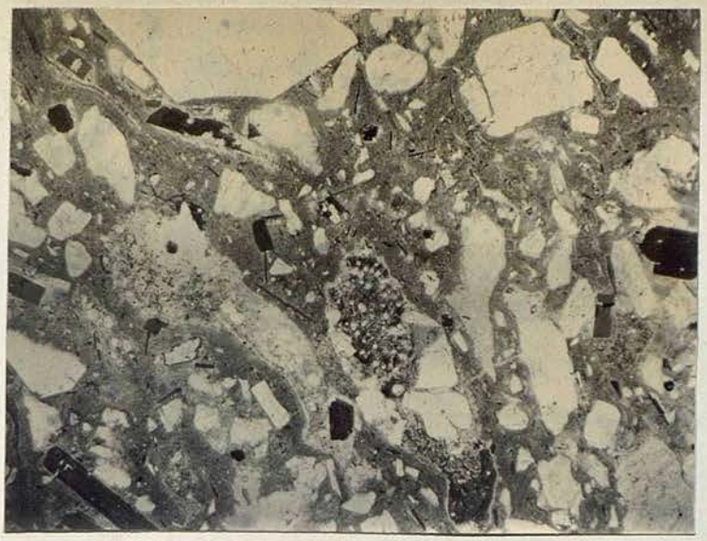
2.

3.

4.

Plate I

Plate II



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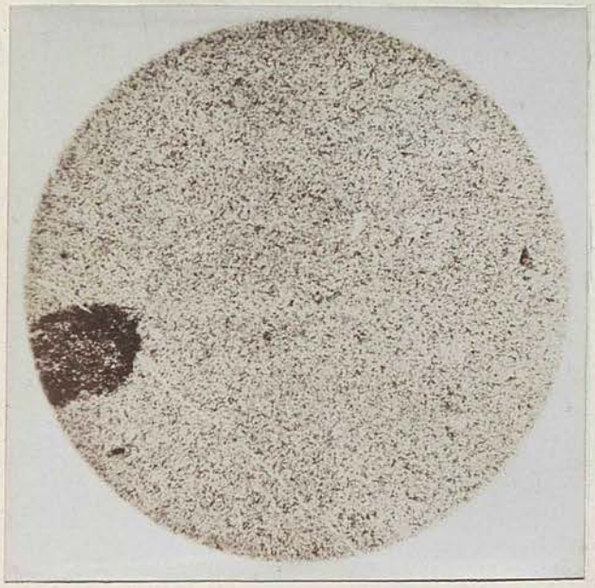

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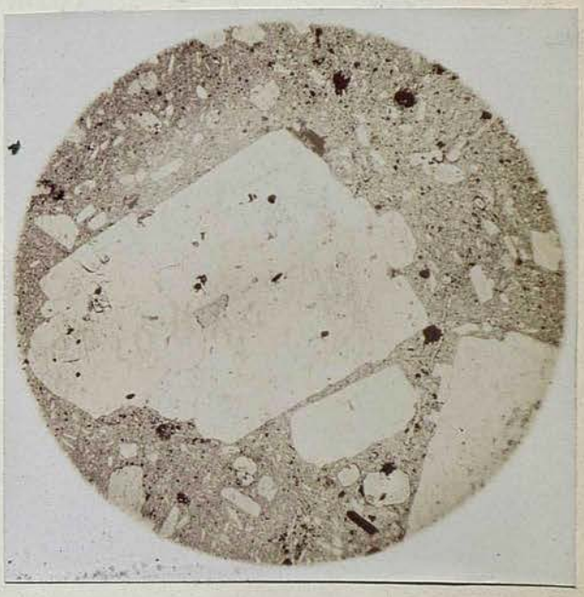

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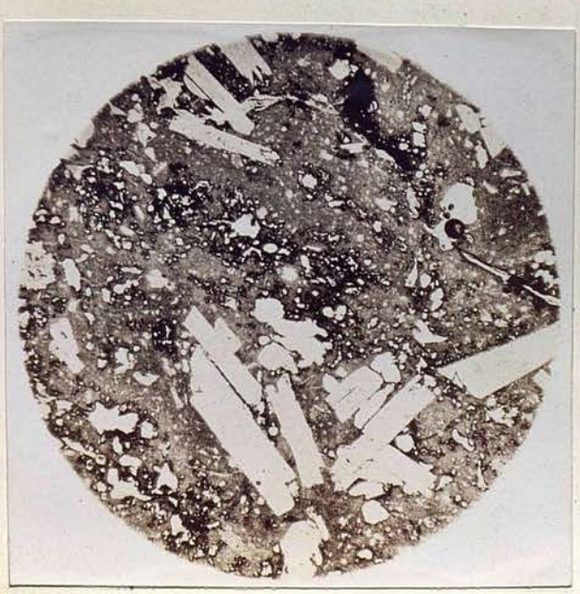

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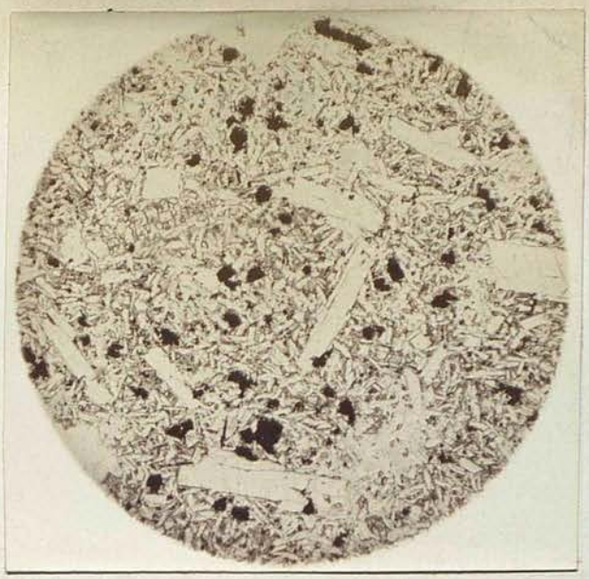
6.

Plate III



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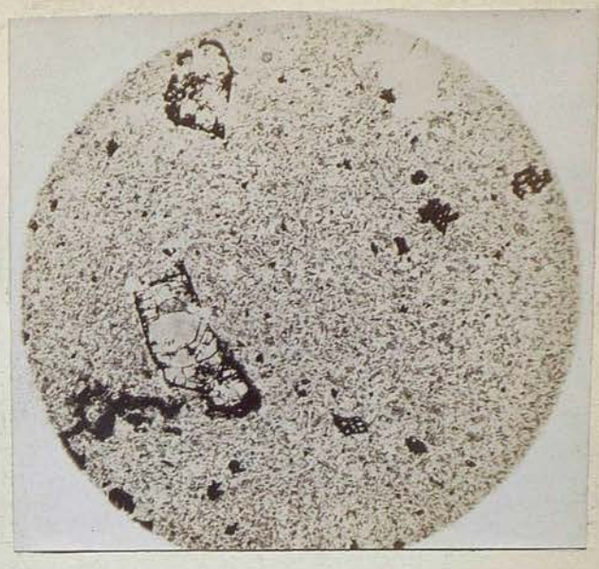

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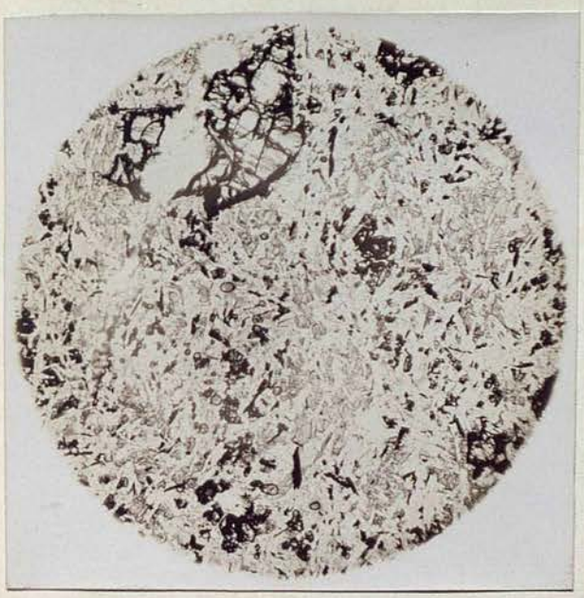

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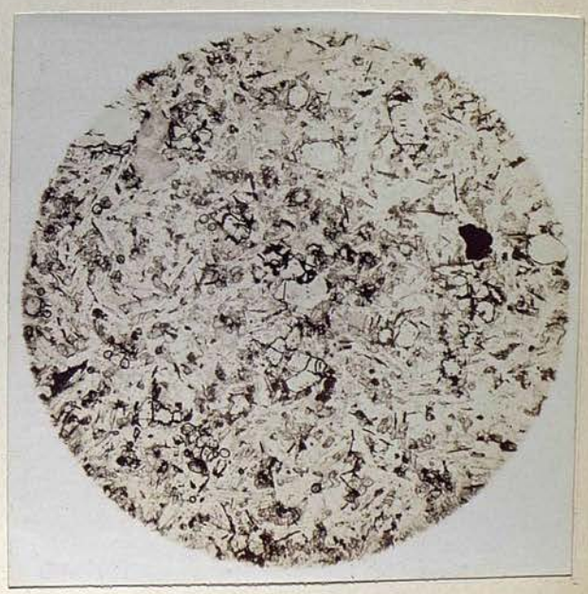

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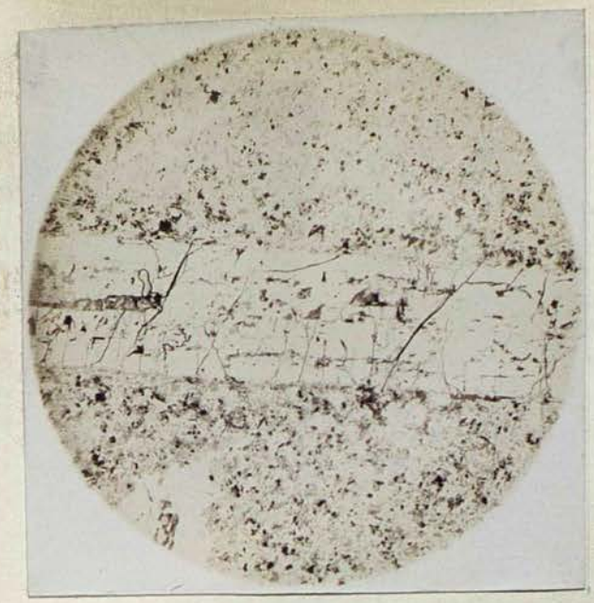
Plate IV



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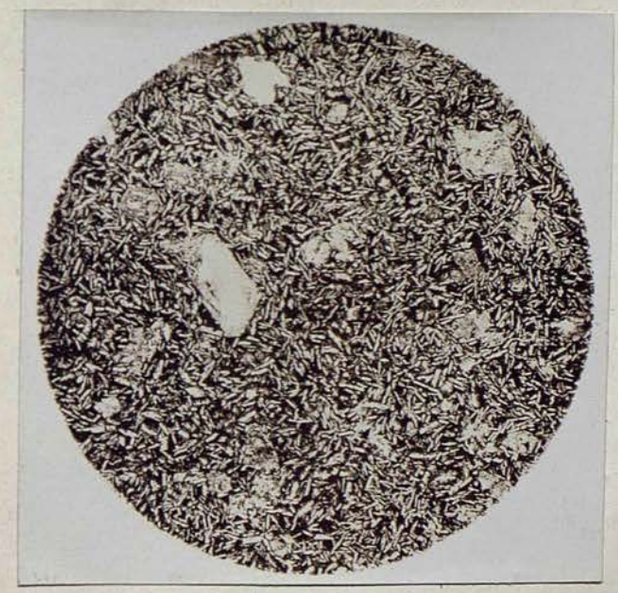

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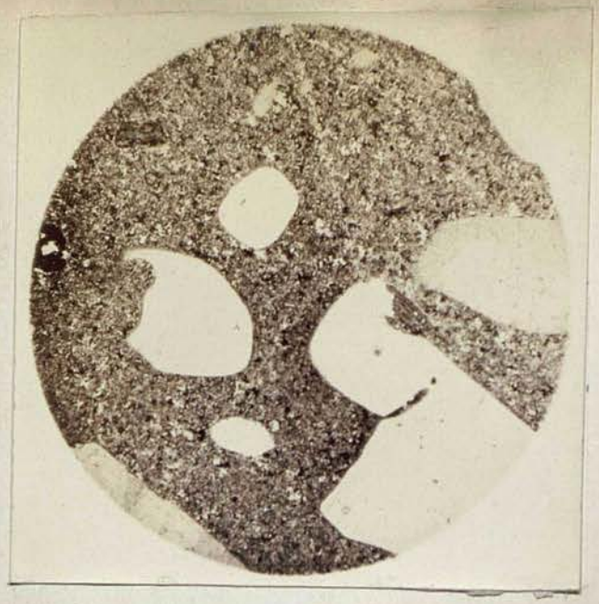
Plate V



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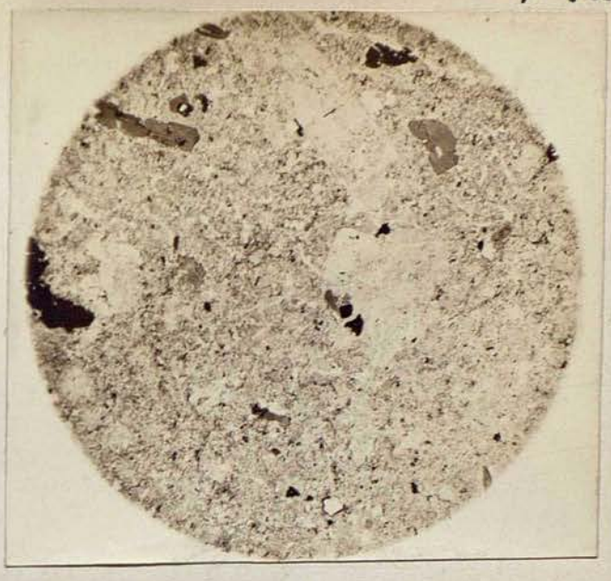

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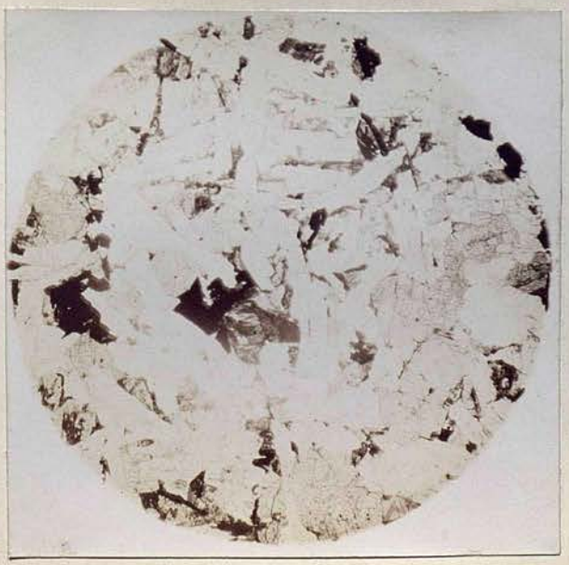

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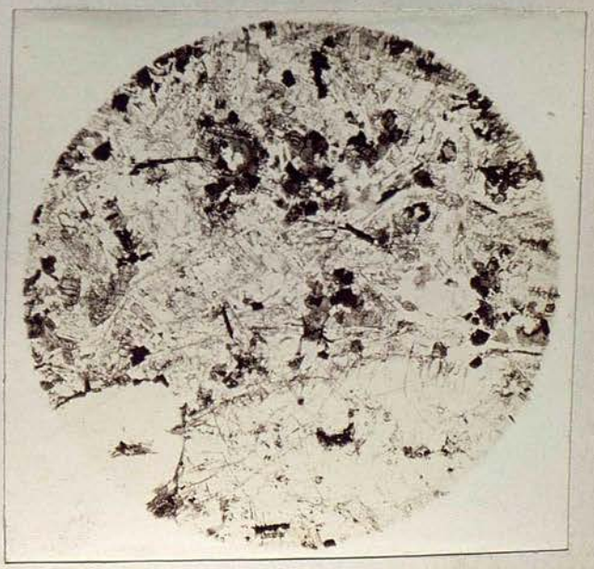
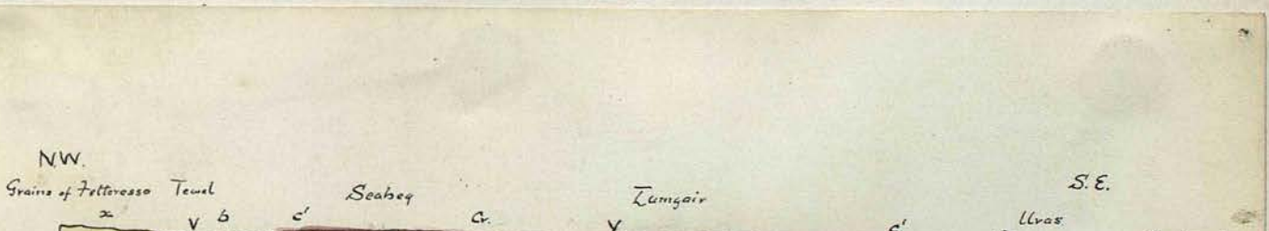


7.

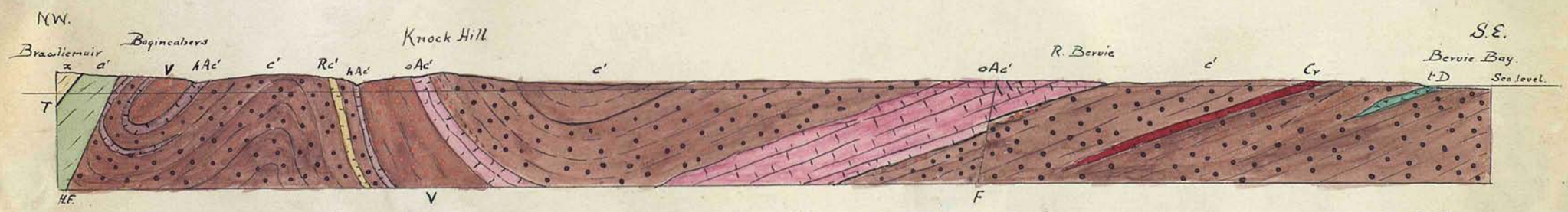
Plate VI

A. Horizontal section from St. Mary's Chapel to Old Kirk Shore, Cowie. Scale. 24 inches = 1 mile.



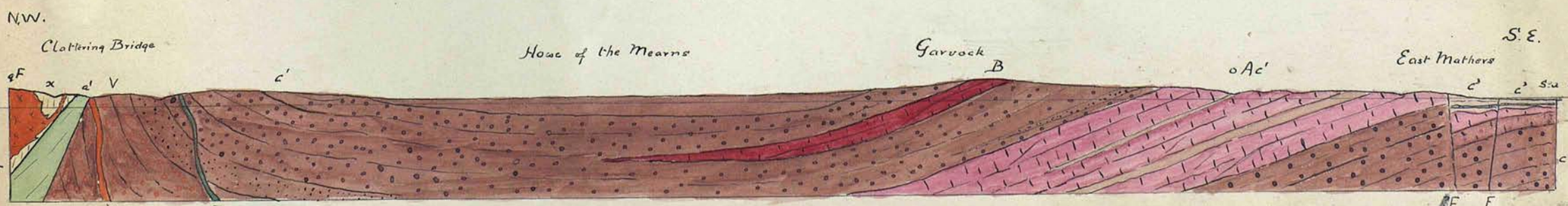
B. Horizontal section from Grains to Uras. Scale 1 inch = 1 mile.

x = Dalradian Schists.
a' = ? Upper Cambrian.
b = Downtonian.
c' = Lower Old Red Sa.
Br = Basement Breccia
V = Volcanic Co. and Tuffs.
Di = Dictyocaris horizon.
Cr = "Crawton" basalt.
U = Unconformity
F = Fault
HF = Highland Fault.



C. Horizontal section from Braeliemuir to Bervie Bay.

Scale 1 inch = 1 mile.



D. Horizontal section from Clattering Bridge to East Mathers.

Scale 1 inch = 1 mile.

x = Dalradian Schists.
a' = ? Upper Cambrian.
c' = Lower Old Red Sa.
V = Volcanic Co + Tuffs.
Rc' = Dacite
hAc' = Hornblende - biotite Andesite
oAc' = Hypersthene andesite + basalt.

Cr = "Crawton" basalt
c³ = Upper Old Red Sa.
qF = Quartz porphyry.
qD = Quartz dolerite
tD = Teschenite
T = Thrust plane

F = fault.
HF Highland fault.

Plate VII

Explanation of geological signs and colours.

Old Red Sandstone

Upper Town

- c^3 — Conestone
- c^2 — Limestone
- c^1 — "Highland" Conglomerate
- c — Volcanic Conglomerate and Tuffs.
- b — "Dictyonema" zone (Upper Silurian / Downtonian)
- Volcanic Co. Tuff.
- a^2 — "Margie" Series
- a^1 — ? Upper Cambrian.
- x — Dalradian Schists

Laws of E. Old Red Sandstone age

Intrusive Igneous Rocks.

- Rc' — Dacite
- hAc' — Hornblende - biotite andesite
- pAc' — Augite andesite
- oAc' — Hypersthene andesite and basalt.
- Bc' — Olivine basalt
- cB — Crawlin basalt.
- qF — Quartz porphyry
- bF — Biotite porphyry
- P — Diorite porphyrite
- L — Lamprophyre
- qD — Quartz dolerite
- tD — Teschenite
- D — Dolerite
- G — Granite.

White lines = Faults

— — T — — — = Thrust Plane.

- Inclined strata.
- Vertical "
- Highly inclined "
- Strike of contorted folding.
- Glacial striae.
- = Uncertain boundaries.


Marqie Series
? Upper Cambrian
Dalradian Schists
Dacite
Hornblende - biotite andesite
Augite andesite
Hypersthene andesite and basalt
Olivine basalt
Granton basalt
Quartz porphyry
Biotite porphyry
Diorite porphyrite
Lamprophyre
Quartz dolerite
Teschenite
Dolerite
Granite
Lavas of L. Old Red Sandstone age
Intrusive Igneous Rocks
White lines = Faults
= Thrust Plane
Inclined strata
Vertical
Highly inclined
Strike of contorted folding
Glacial striae
= Uncertain boundaries
Fettercairn
Laurencekirk
Arbuthnott
Forfar
Brechin
Montrose
Edzell
Stracathro
Logie Pert
Marykirk
Johnshaven
Milton Ness
Hill of Gothie
Goyle Hill
Boy's Hill
Meikle Calf Hill
Meluncart
Kircram
Cairn o' Mount
Thorter Hill
Hill of Annahar
Loch Hill
Redstone Hill
Hound Hillock
Shank of Cardowan
Arnbarrow Hill
Herd Hill
Cock Hill
Rough Bank
Hen Hill
Gaerlie
Drumlithie
Garvock Hill
Bervie Bay
Kinneff
Catterline
Inverbervie